A Study of the Group-IV Diluted Magnetic Semiconductor GeMn

Melissa Commisso Dolph

Stu Wolf Group

December 4th, 2008

UNIVERSITY of VIRGINIA
Institute for Nanoscale and Quantum Scientific and Technological Advanced Research
nanoSTAR

Outline

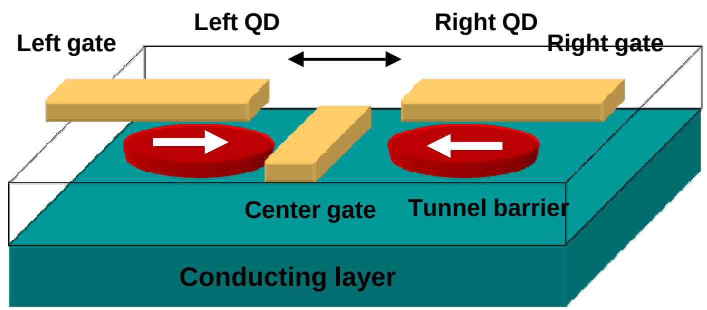
- Motivation and Background
- Our DMS：GeMn
- Hall Bars
- Summary ／ Future Work

Motivation

- Moore's Law reaching its limits
  - Size of circuit elements scaling into a regime where leakage impedes functionality

- Search for successor to conventional CMOS
  - e− spin as state variable to develop new technologies that can be incorporated with or replace CMOS
    - Benefit of lower power dissipation

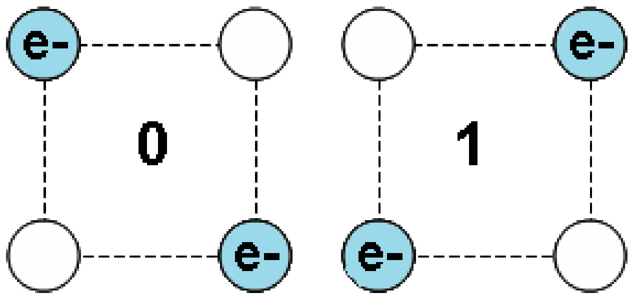
- Our goal is to create a spin based logic/memory device using magnetic quantum dots (MQDs)
  - We will be studying the diluted magnetic semiconductor GeMn
    - Understand the magnetism
    - Control the magnetism
      - Mn implantation
      - Electrically



Magnetic Exchange Switch with 2 MnGe QDs

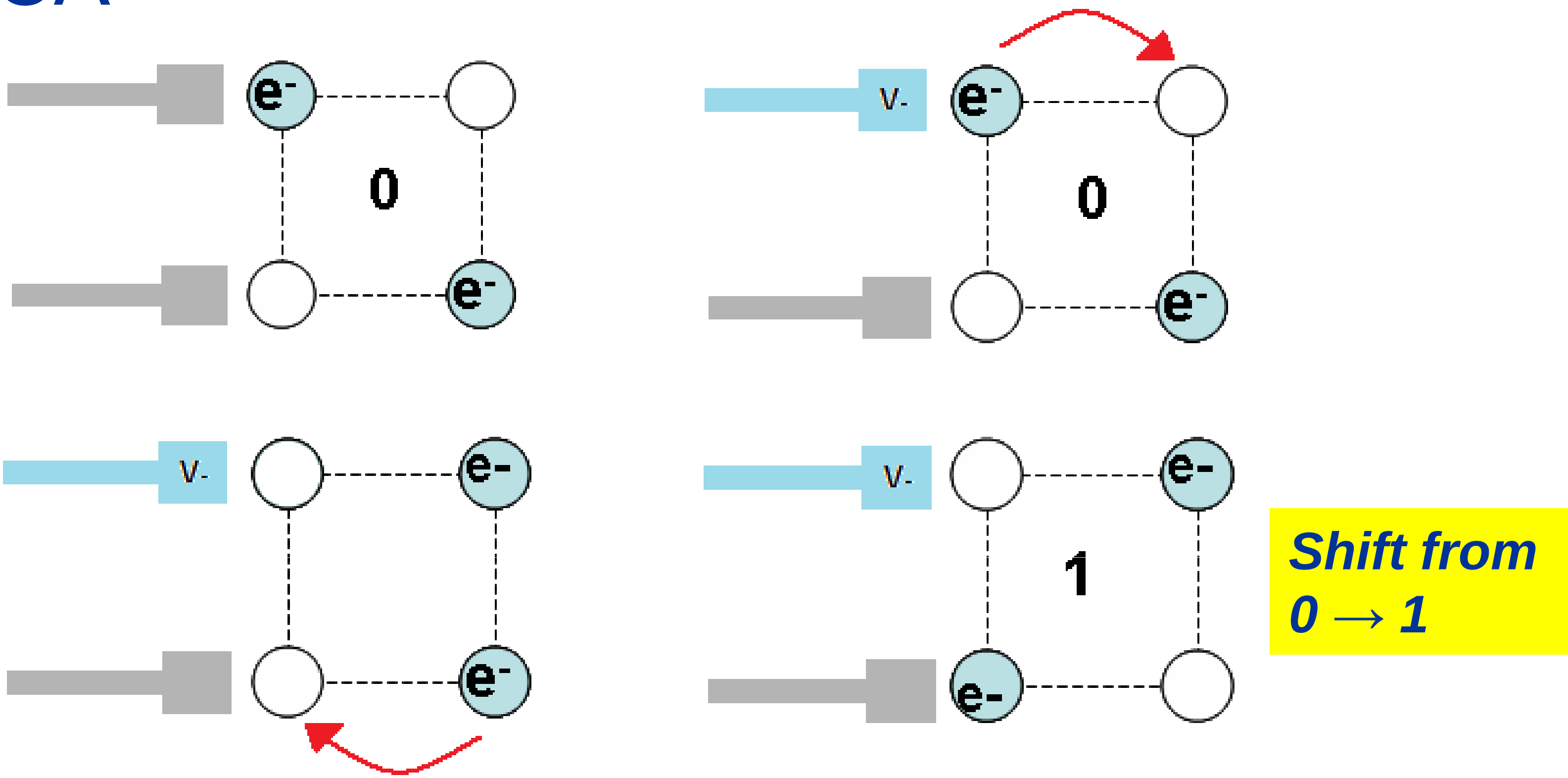
Background Concepts for a MQD Device: Quantum-dot Cellular Automata (QCA)

- QCA: uniform grid of cells, simplest model has 4 QDs arranged in a square
- e-s can tunnel into QDs, and arrange themselves into lowest energy states



- QDs respond to charge states of neighbors ⟶ writing

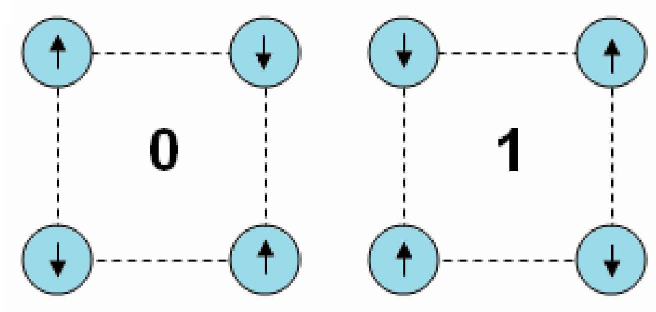
QCA



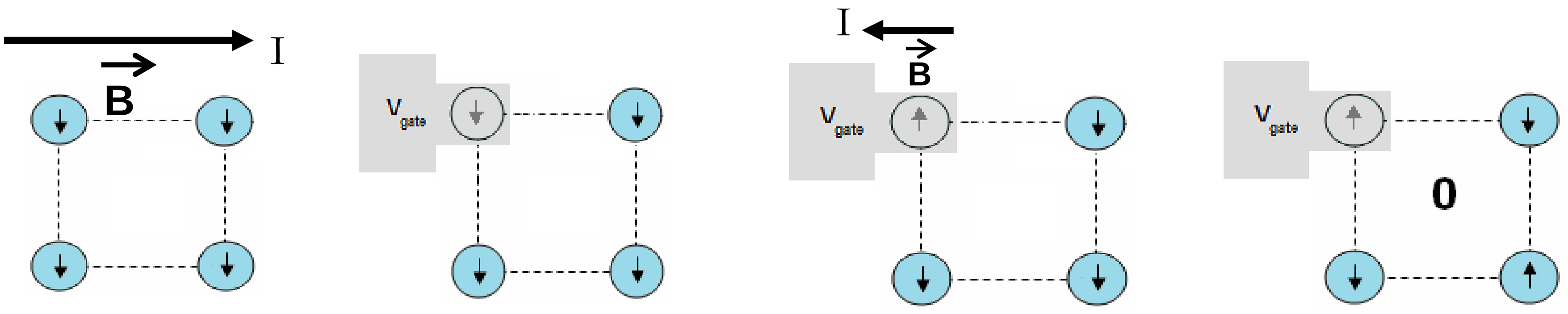
- Read–out: Quantum Point Contact, Single Electron Transistor
  - QPC: changes in conductance, SET: changes in capacitance due to single e–

Magnetic QCA (MQCA)

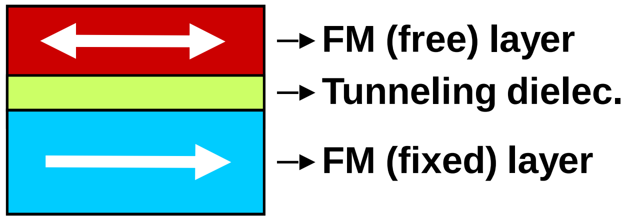
- Magnetic QDs (MQDs): control carrier spin and interactions between carriers
- Gated control of MQDs
  - Carrier concentration and state
- Coupling b/w dots
  - Lowest energy, Pauli exclusion



MQCA

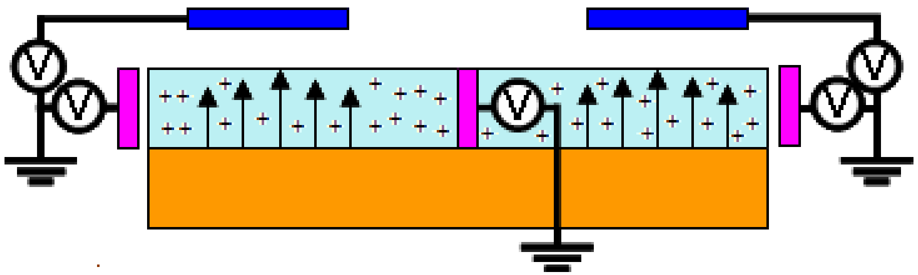


- Read−out: Magnetic Tunnel Juntion
  - Free layer magnetized by external field
  - Applying small bias voltage creates tunneling current thru dielectric
  - Switch direction of free layer, remeasure current
  - Relative size of current gives state of fixed layer (larger current → smaller MR→ parallel orientations)



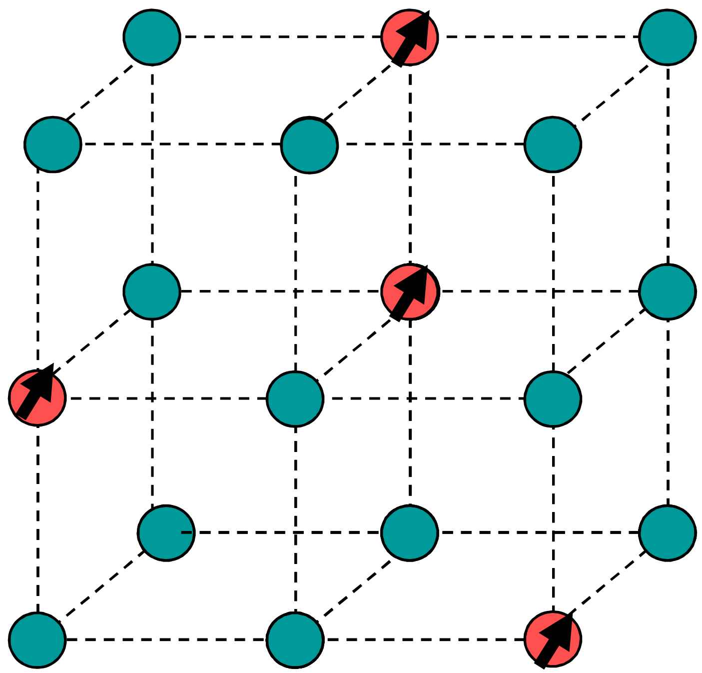
Magnetic Spin Switch

- Electrically controlled interactions between MQDs
  - Blue features are QDs
  - + are holes
  - Arrows are (Mn) spins
- Side gates -- carrier concentration and adjacent spin coupling
  - Ferromagnetic vs. anti-ferromagnetic behavior
- Top gates -- read-out
  - MTJ between top gate and QD yield MR which gives spin orientation



What is a Diluted Magnetic Semiconductor?

- Portion of semiconductor atoms (Si, Ge, GaAs) replaced with magnetic atoms (Mn, Fe, Co)

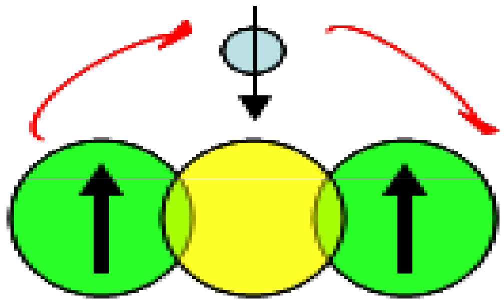


- Mn atoms introduce
  - Spins
  - Holes (mediate coupling b/w spins)

  → *Ferromagnetic behavior*

DMS Magnetic Interactions

- *Ferromagnetic* behavior between nearby Mn
  - Long range ferromagnetic (FM) behavior dominates short range anti-FM behavior
  - Zener double exchange – Mn spin couples to nearby hole, which is also coupled to another Mn spin (not nearest neighbor)

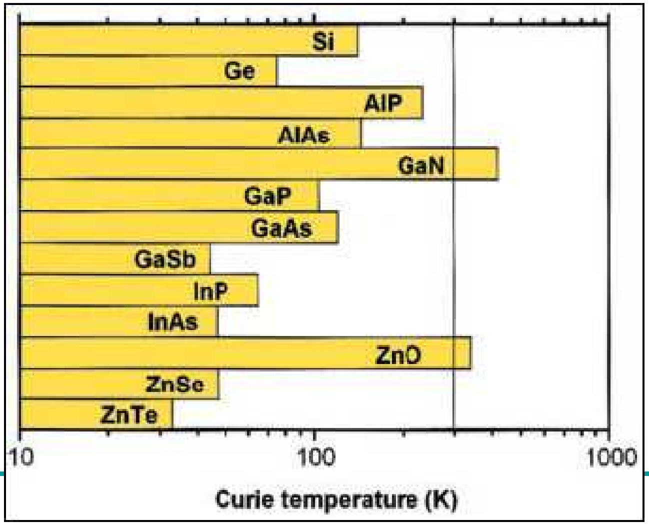


The DMS GeMn

- Hole mediated FM exchange
- Temp dependence of resistivity has semiconducting characteristics
- T_{Curie} ↑ linearly (26 – 116K) with ↑ Mn concentration (0.6 – 3.5%)
- Success in electrical modification of FM in other materials, but T_{Curie} too low
  - Example: Group III–V GaMnAs, T_{Curie} ~ 170–180K

- Ge shows promise
  - Higher hole mobility than GaAs and Si
  - +/– 0.5V gates control hole density compatible with CMOS technology
  - Zener model shows “high” T_{Curie}

Computed T_{Curie} for various p-type semiconductors containing 5% Mn and 3.5 x 10^{20} holes/cm^3



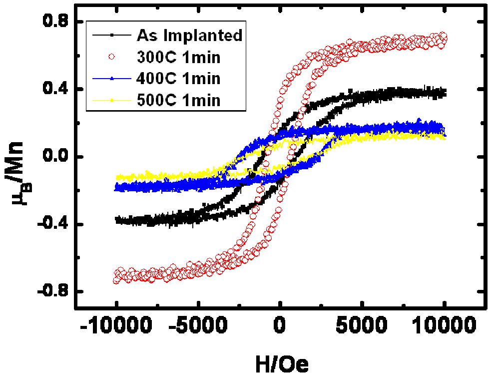
Reference: *Park et al., Science* ***295****, (2002)*

Dietl et al., Science ***287****, 1019 (2000)*

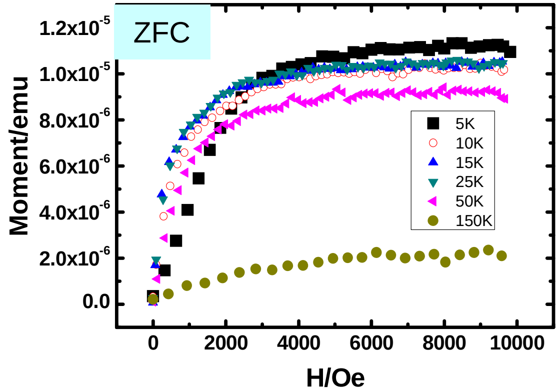
GeMn – Magnetism

Forms of magnetism: *ferro*–, *para*–, *superpara*– magnetic

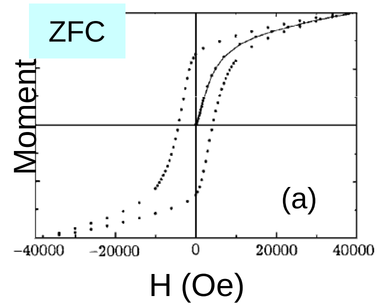
- Moment vs. Field:



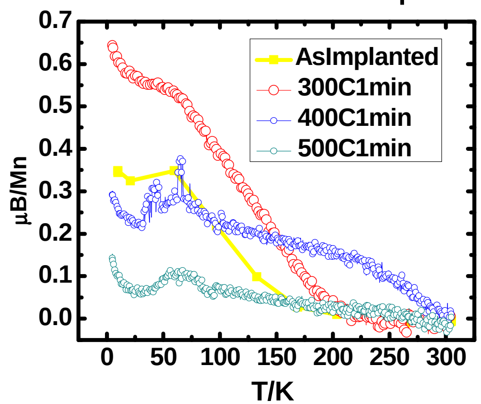
- Ferromag signal
  - Mn concentration
  - anneal conditions
- Saturation moment
- Coercive field



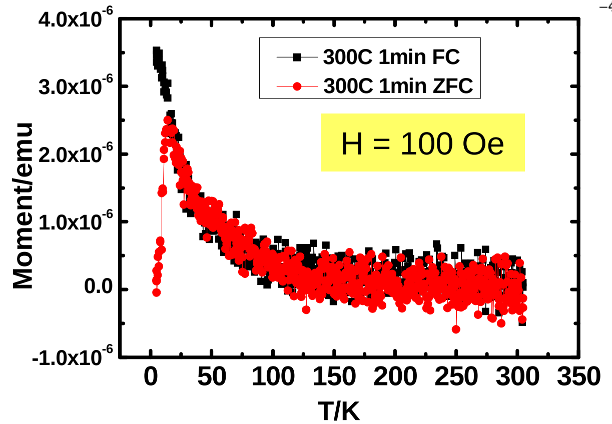
- Virgin curves (0 → 1T) show evidence of shift from FM to SPM



- Moment vs. Temperature:



- T_{Curie}
- Transition temps

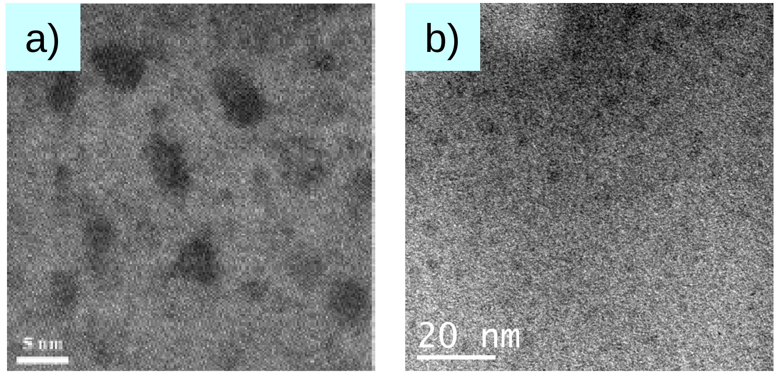


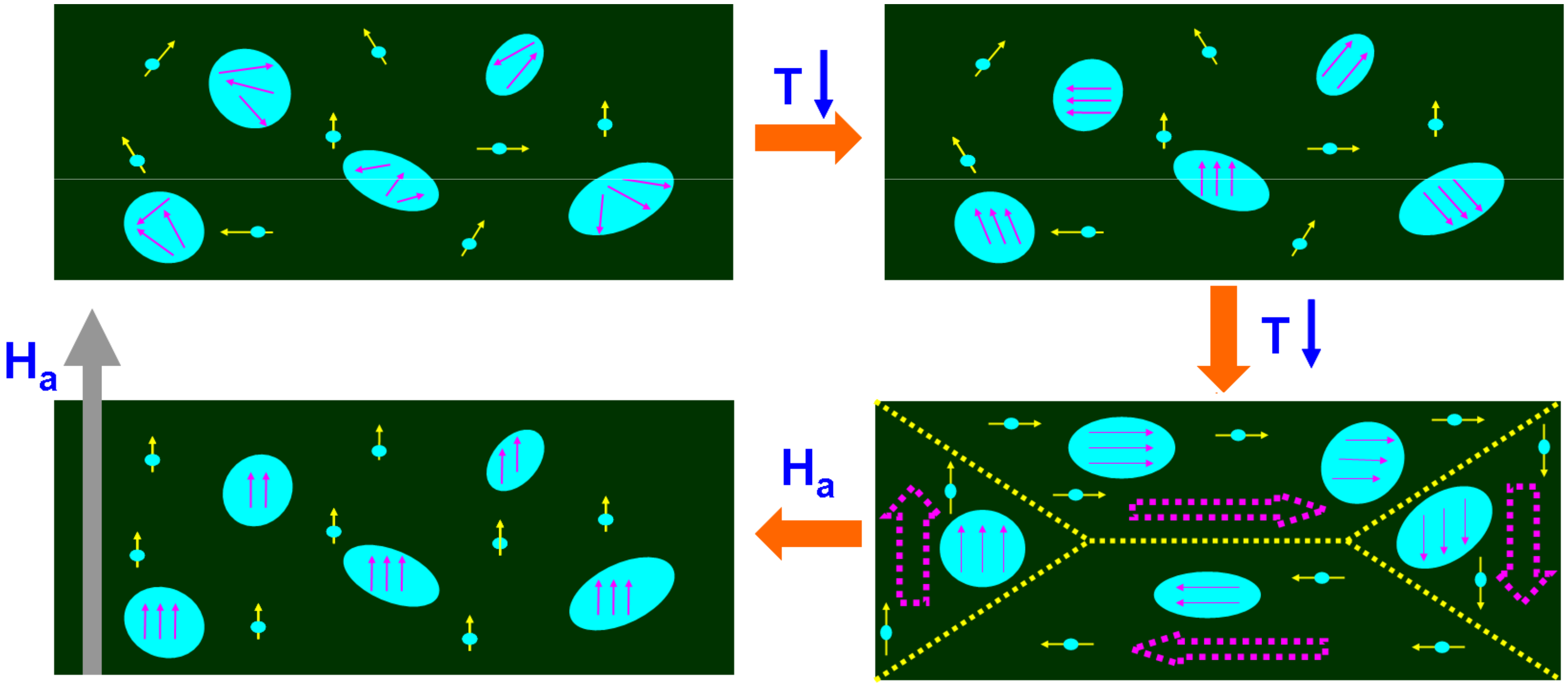
- Field cooled (FC) and Zero-Field Cooled (ZFC) curves diverge at T_{Curie}

Work done by Wenjing Yin

(a) Deng-Lu et al, Chinese Physics, 2002

GeMn – Magnetism





Picture courtesy of Wenjing Yin

TEM images:
a) Bougeard et. al. PRL, 97, 237202 (2006)
b) Li He, Robert Hull (UVA / RPI)

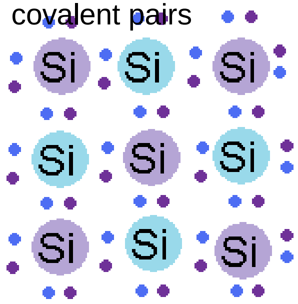
Outline

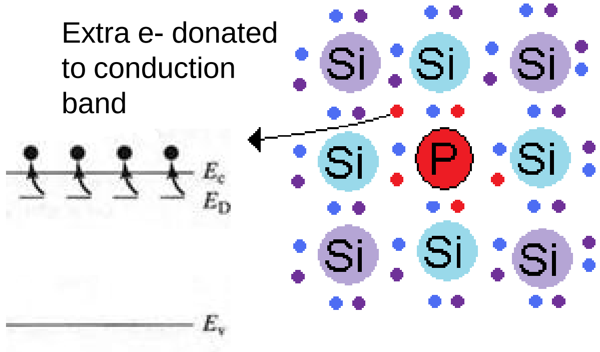
- Motivation and Background
- Our DMS: GeMn
- Hall Bars
- Summary / Future Work

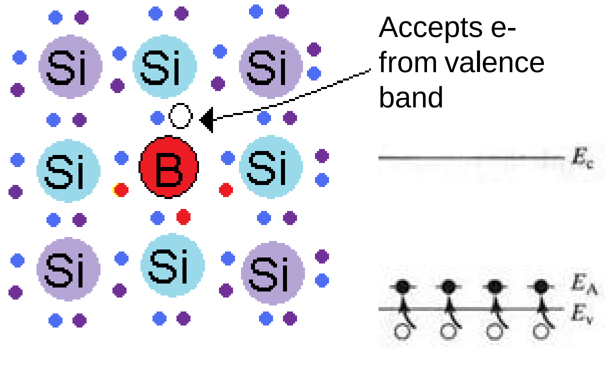
GeMn – Doping

MnGe	200nm
SiO_2	400nm
Si	525µm

Si, Ge atoms have 4 valence e-'s
Nearest neighbors form covalent pairs

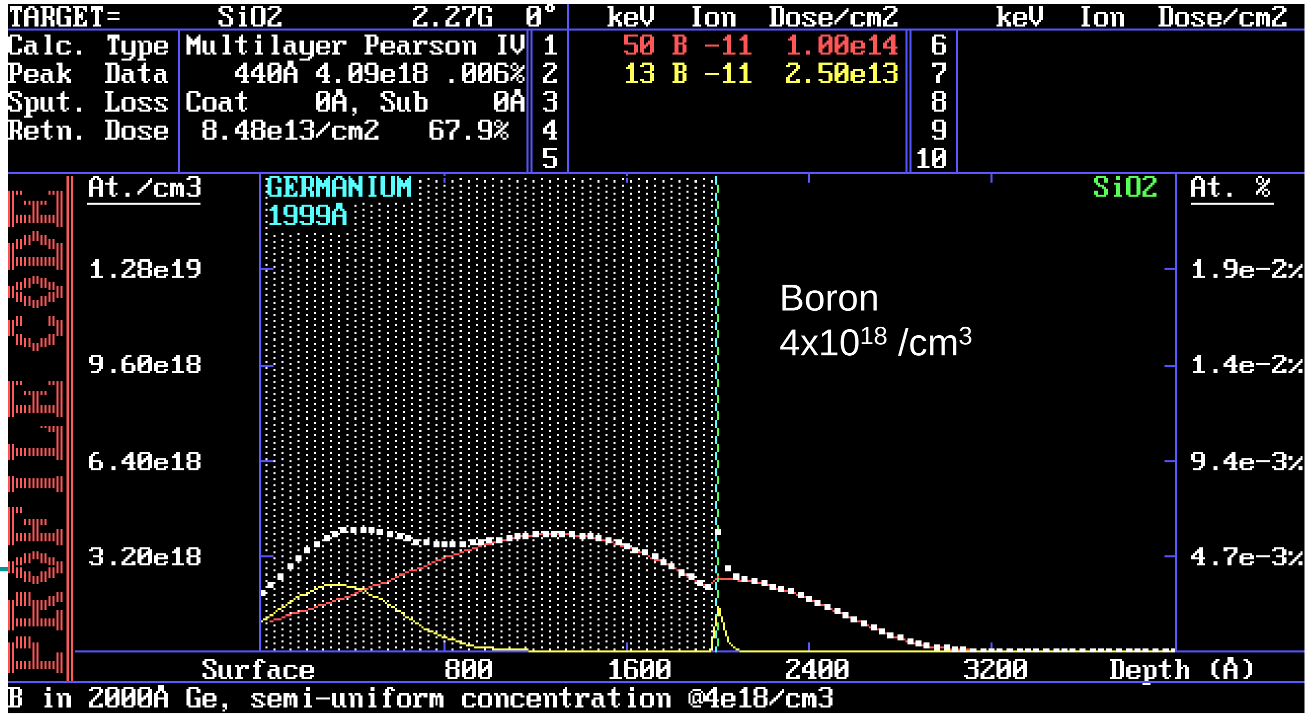






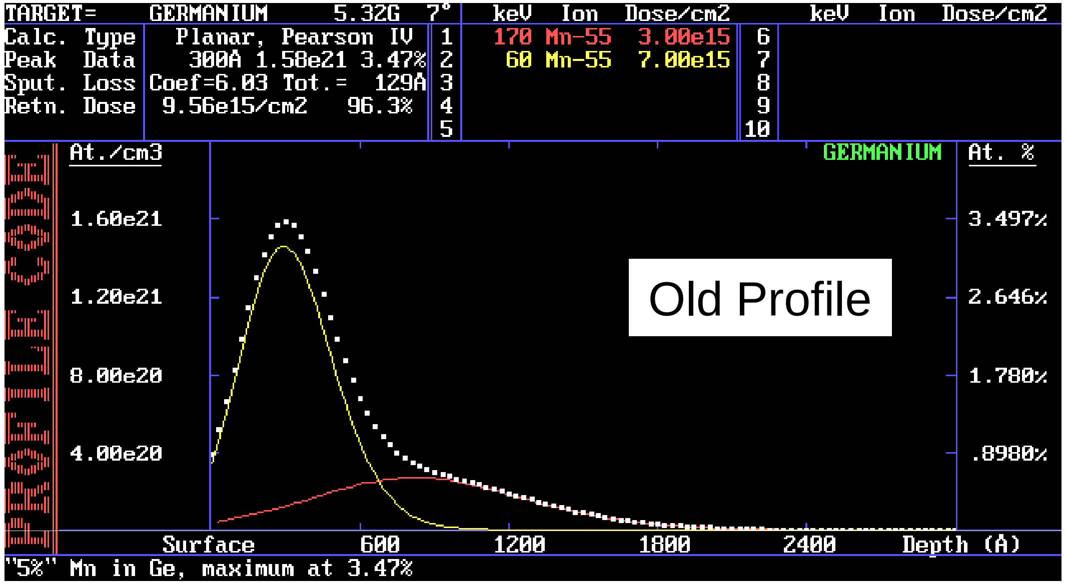
Doped n−type（Phosphorus)

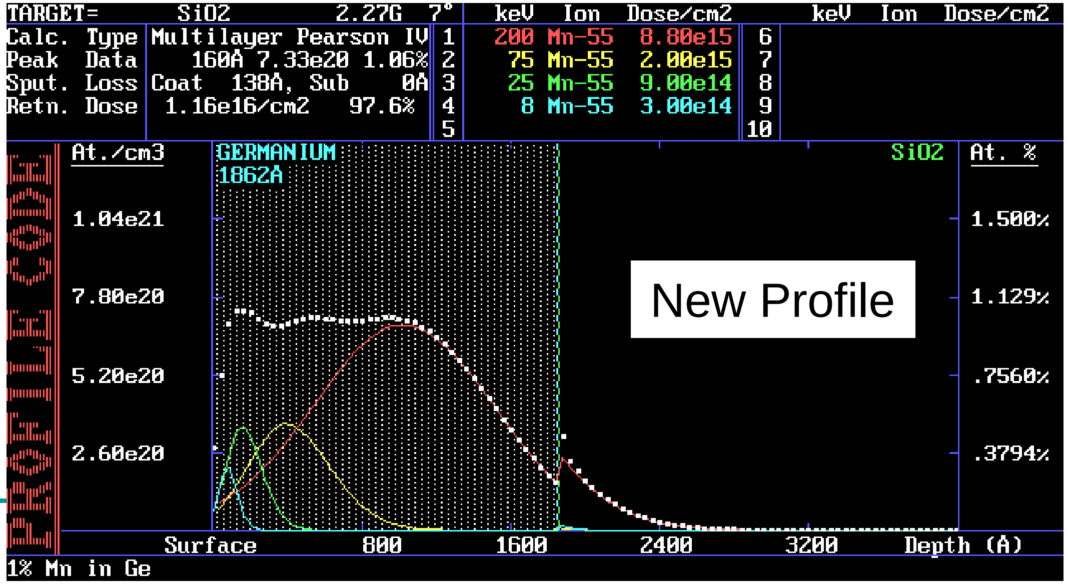
and p−type（Boron)



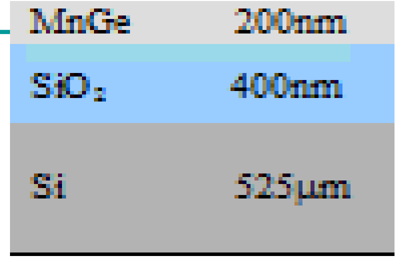
GeMn – Mn Implantation

- Ion implantation is the method used to introduce Mn into the Ge lattice
- Multiple implantations yield more uniform distribution
- Implantations done at low temp (75°C) to avoid formation of secondary phases

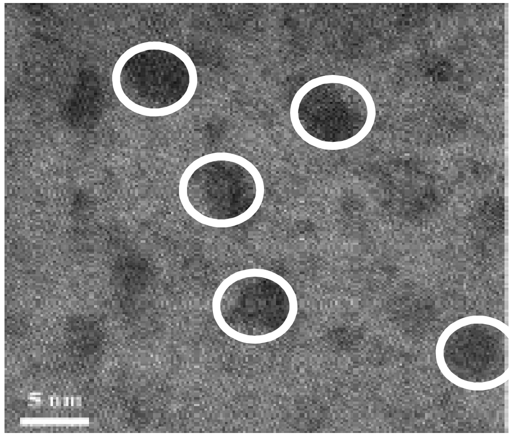




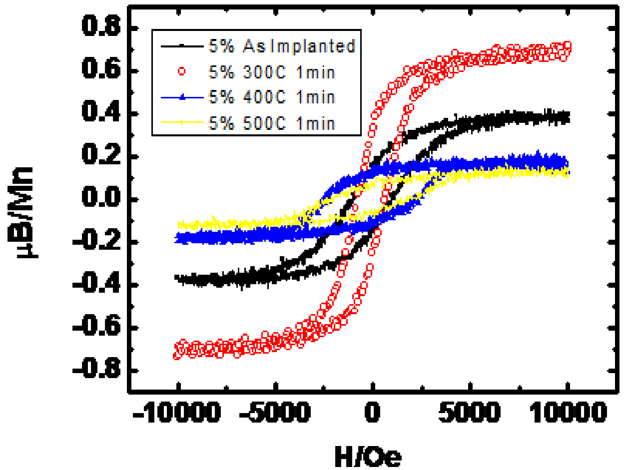
GeMn – Rapid Thermal Anneal



- Mn implantation damages crystallinity of Ge film
- Mn tends to cluster

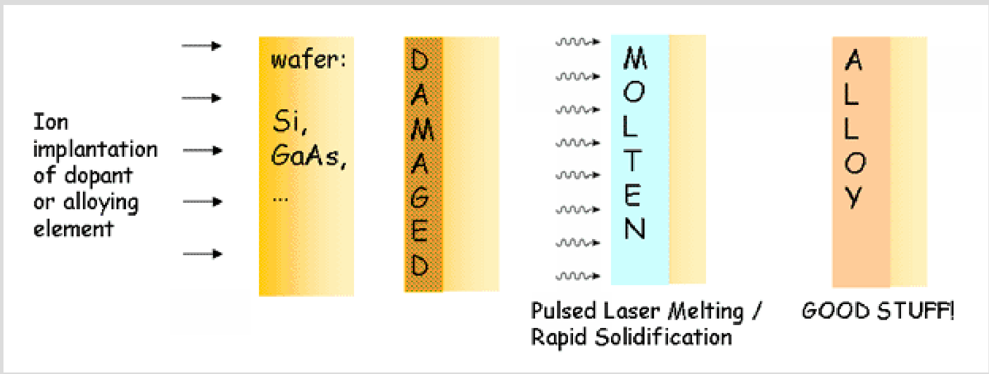


- Rapid Thermal Anneal (RTA)
  - Recovers implantation damage
  - Redistributes Mn
  - Annealing temp affects saturation moment and T_{Curie}



Plot courtesy of Wenjing Yin

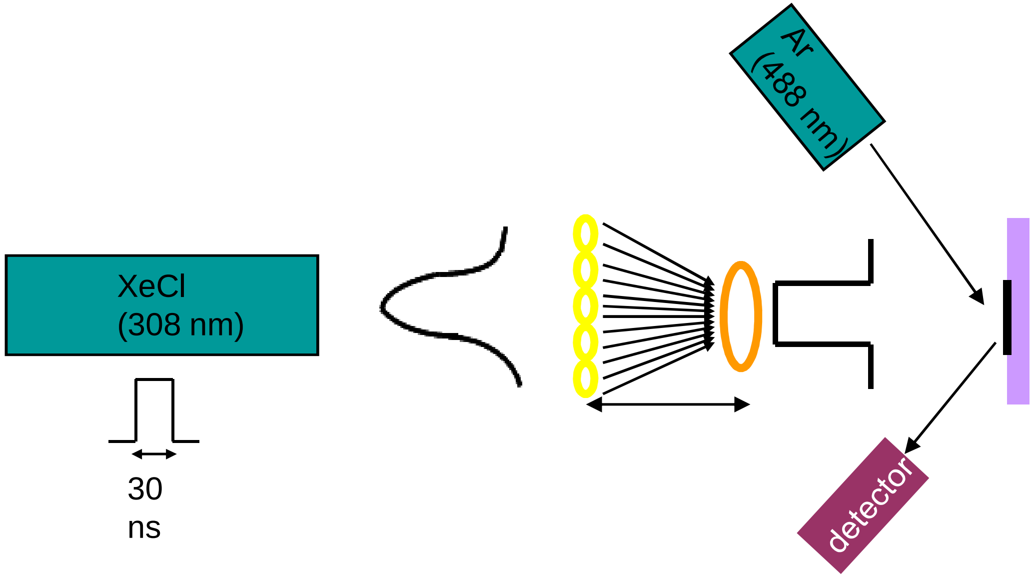
GeMn – Pulsed Laser Melting

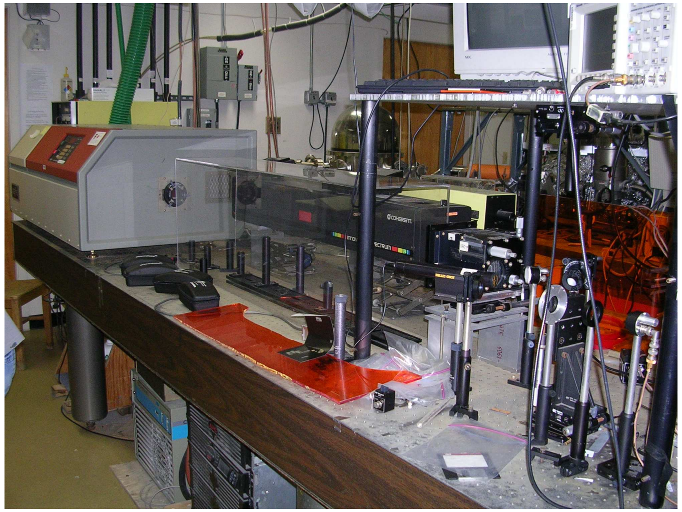


Picture from Prof. Michael Aziz's website

- Film becomes damaged after implantation
- Laser melts film, which quickly (~100 ns) solidifies as crystalline material

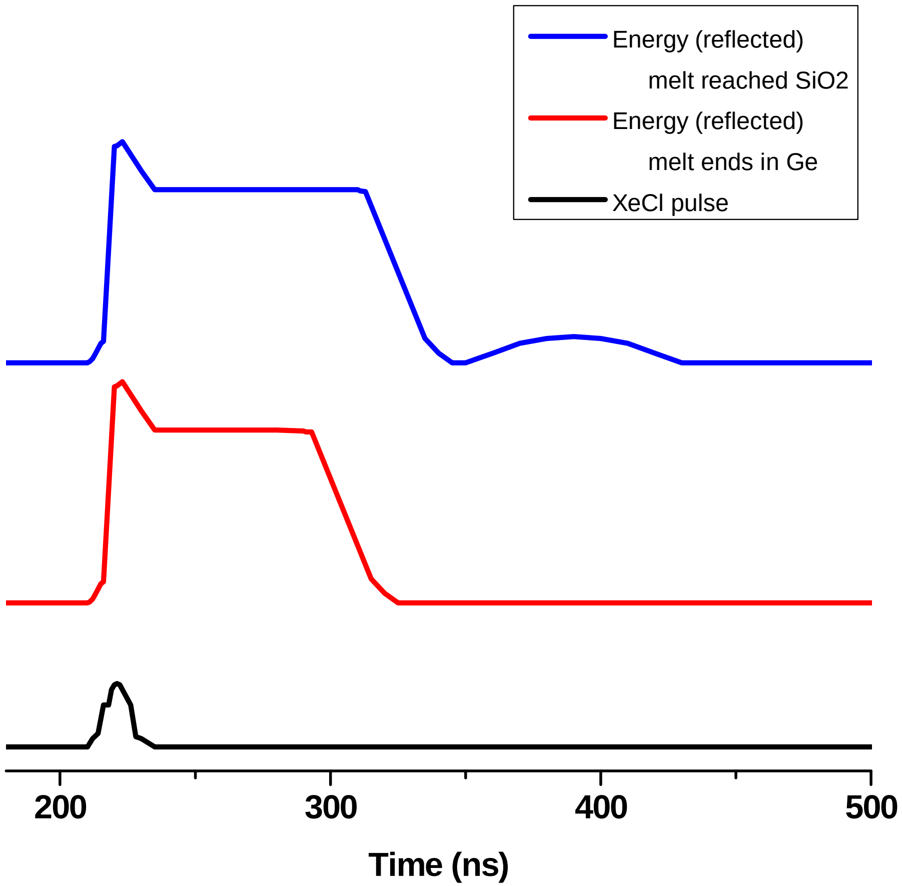
- Helps avoid clustering and secondary phases
- Shows better recrystalization than RTA





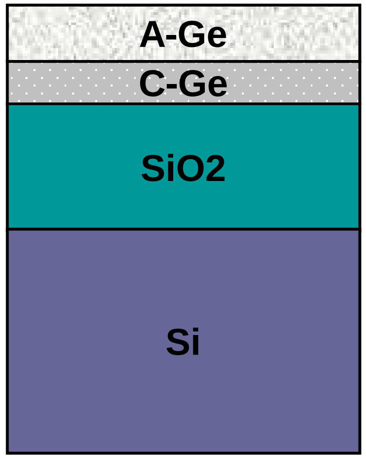
Prof. Aziz's lab, Harvard

Pulsed Laser Melting

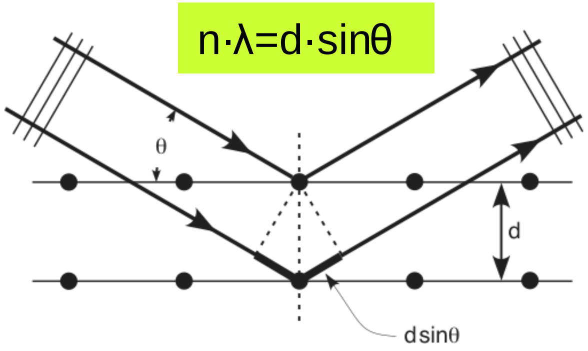


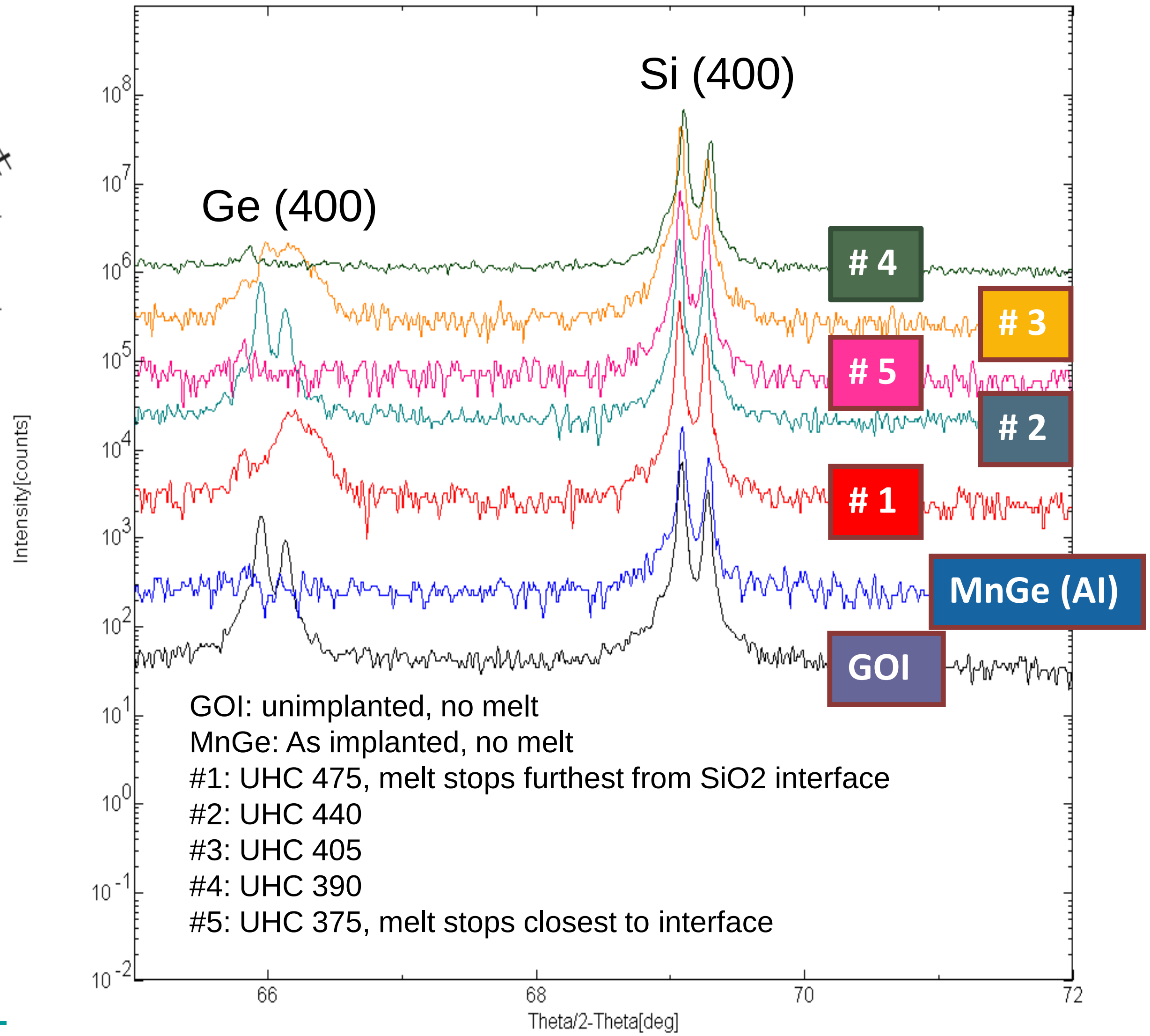
- Melt needs to end in crystalline Ge region so that there is a seed layer for Ge to recrystallize

- Melt depth determined by beam fluence (energy/spot size)



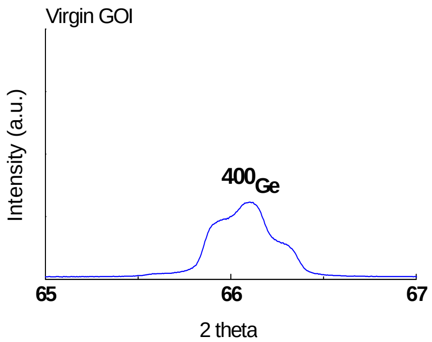
PLM : X−Ray Diffraction

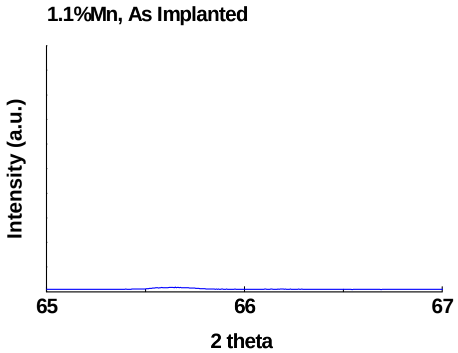


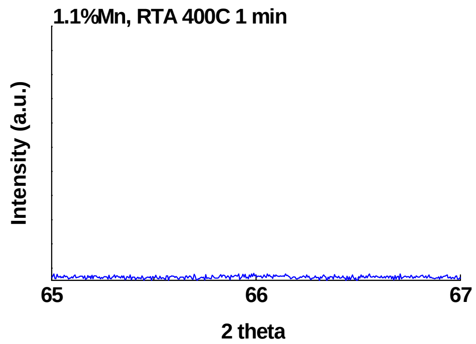


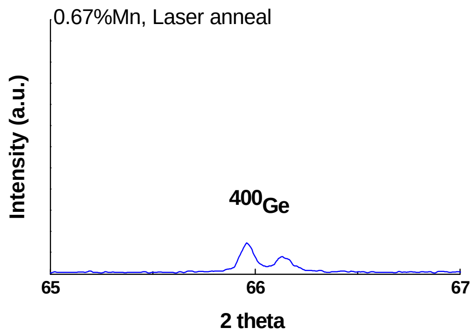
PLM : Comparison of Results

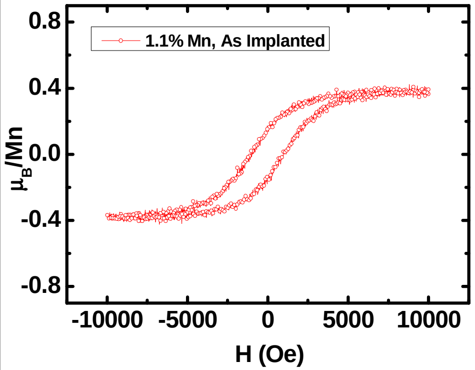
GOI	As Implanted	RTA	PLM

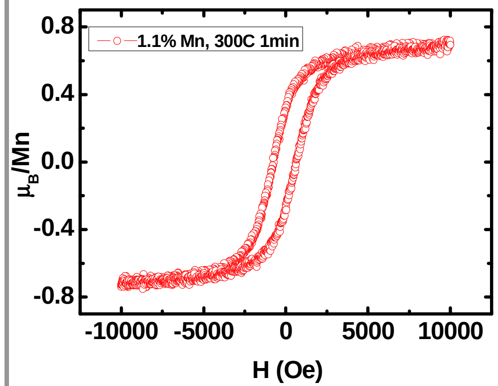


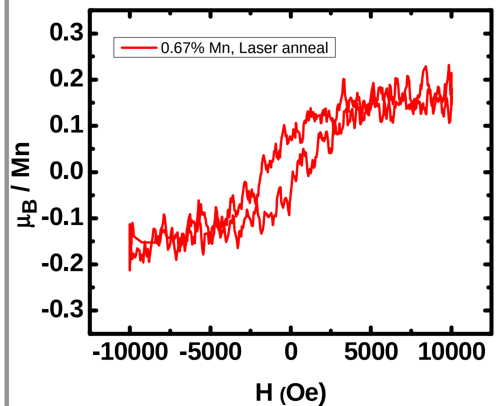










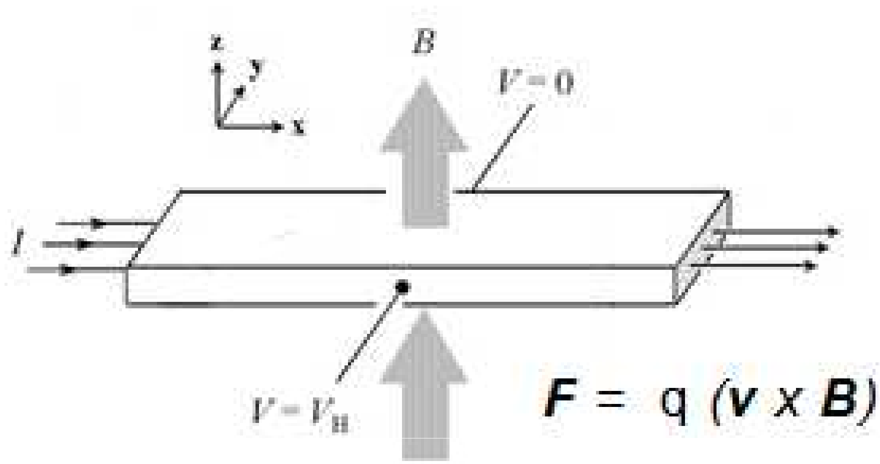


(M vs. H data at 5K)

Outline

- Motivation and Background
- Our DMS: GeMn
- Hall Bars
- Summary / Future Work

Hall Effect



- Charge build up on 1 side creates potential difference
- Comprised of ordinary and anomalous Hall effects (OHE, AHE)

$$V_{Hall} \propto \alpha B + \beta M$$

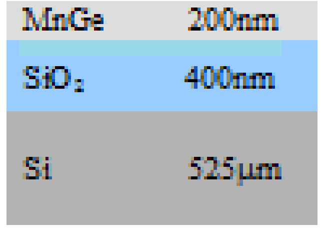
OHE AHE

(α, β are cor... ...epend... film dimensions, sheet resistance (resistivity/thickness), and applied current)

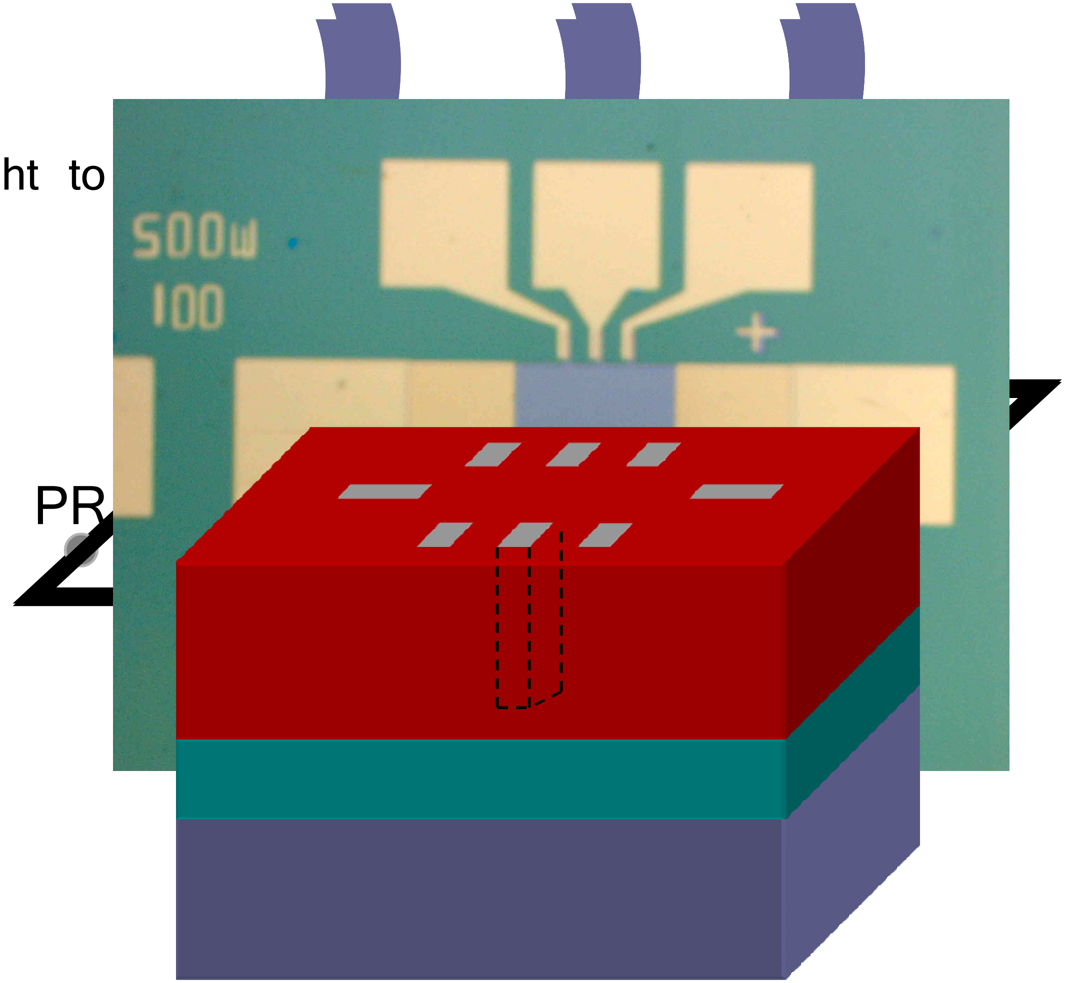
- AHE can be extrapolated
  - Proportional to magnetization

- Hall potential gives additional info:
  - Sign of Hall potential $\rightarrow$ n- or p- type semiconductor
  - $R_{Hall} = V_{Hall}\, A \,/\, I\, \ell\, B = 1 \,/\, nq$ $\rightarrow$ n = carrier concentration (cm^{-3})

Hall Bar Fabrication

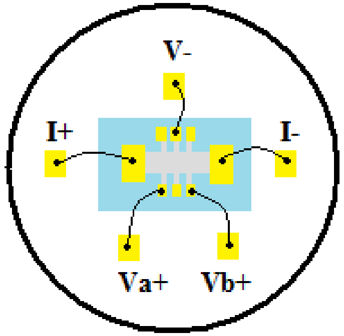


- Start with GeMn thin film
- Spin on photoresist
  - Chemical, reacts with UV light to become soluble/insoluble
- Expose using mask
- Develop
- Etch exposed Ge; Remove PR
- Anneal
- Pattern contacts
- Evaporate metals

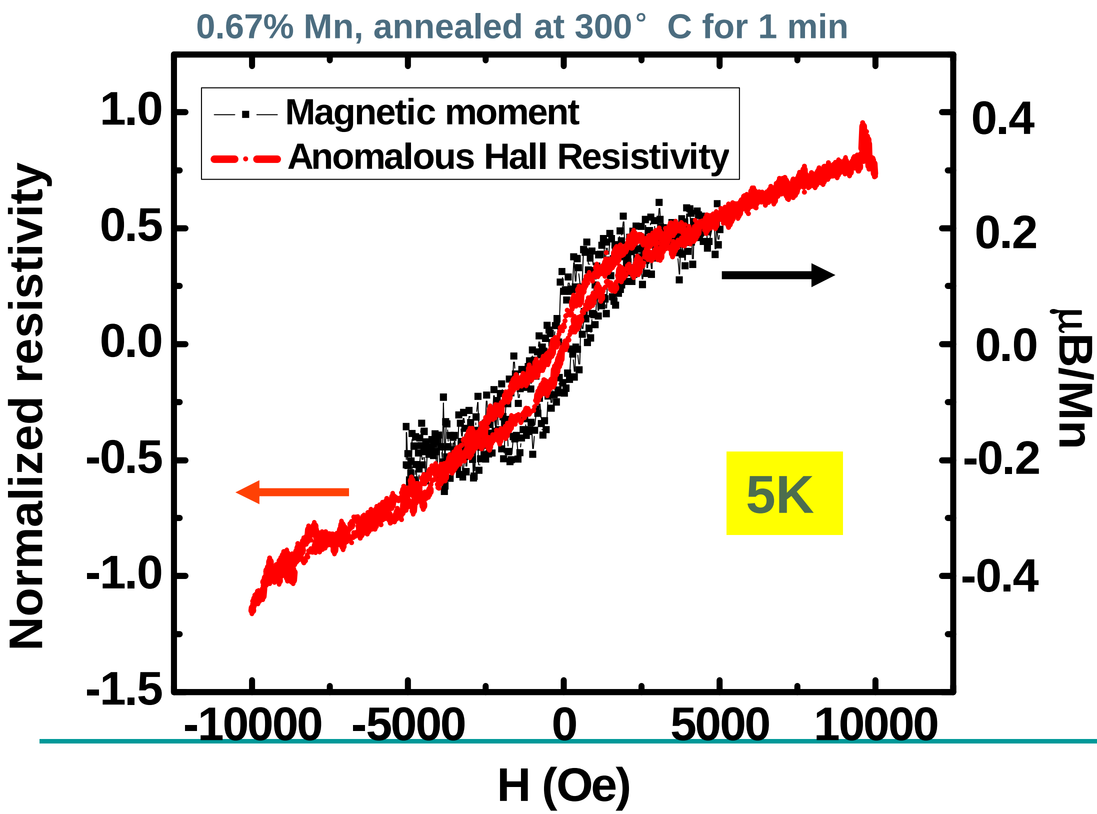


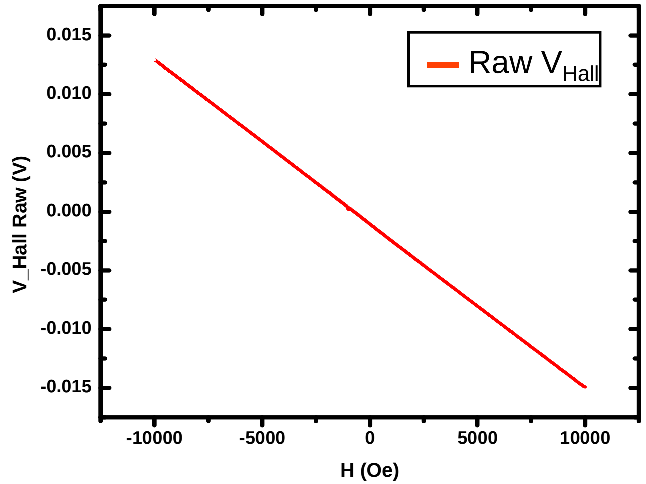
Measurement – AC Transport

- 5 point contact
  - If voltage leads are not perfectly ⊥ to bias field, measured voltage has additional components (besides V_{Hall})
  - Without B field, potentiometer b/w Va+ and Vb+ nulls offset voltage due to sample resistance



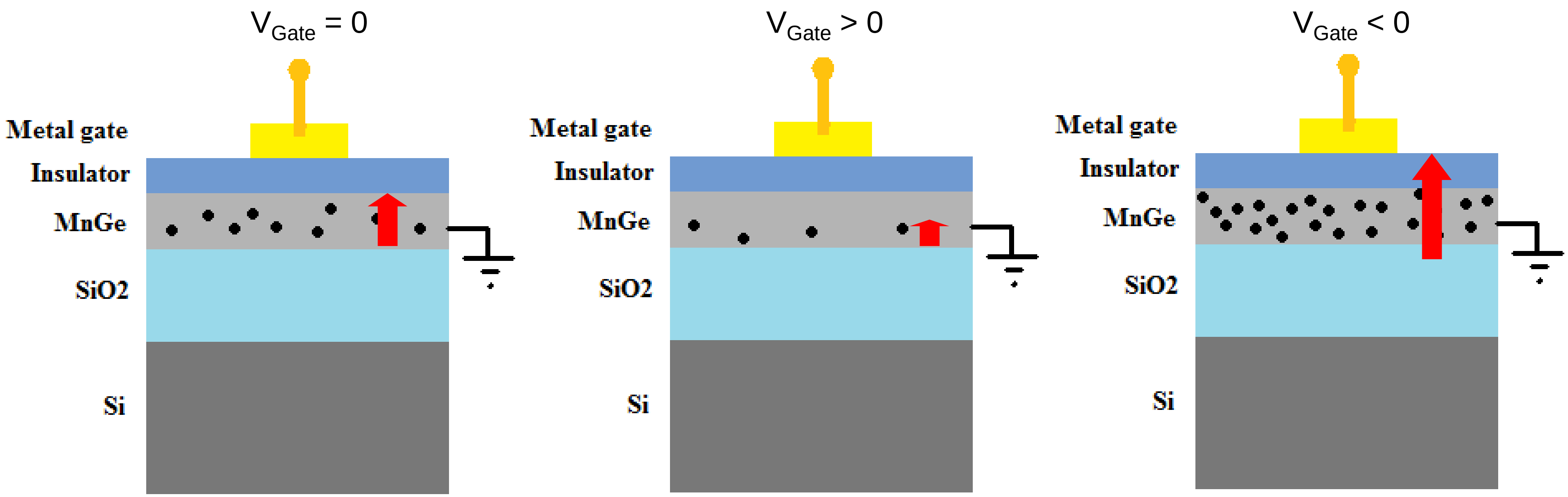
- OHE dominates at high field: Can be subtracted out





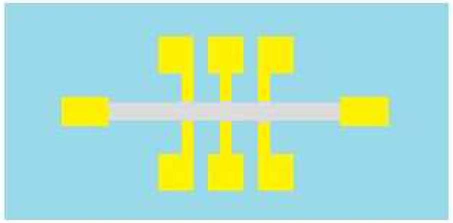
Electrical Control of FM

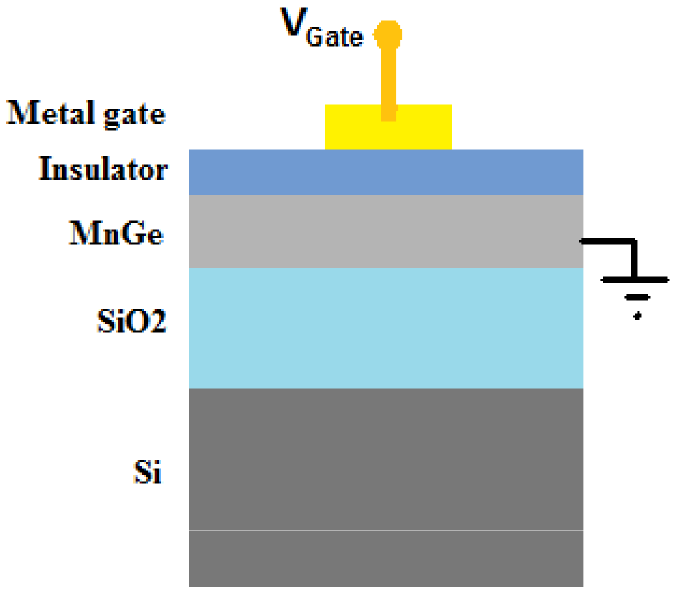
- How do electric fields control the FM?
  - Voltage applied across MOS structure modifies charge distribution in semiconductor
    - P- type semiconductor:
      - V > 0 creates depletion layer by forcing (+) holes away from insulator/semiconductor interface creating carrier-free region
      - V < 0 attracts holes to interface
  - Carrier mediated FM, so strength of FM dependant upon carrier concentration



Electrical Control of FM: Gated Hall Bars

Work done at UVA, CNS:



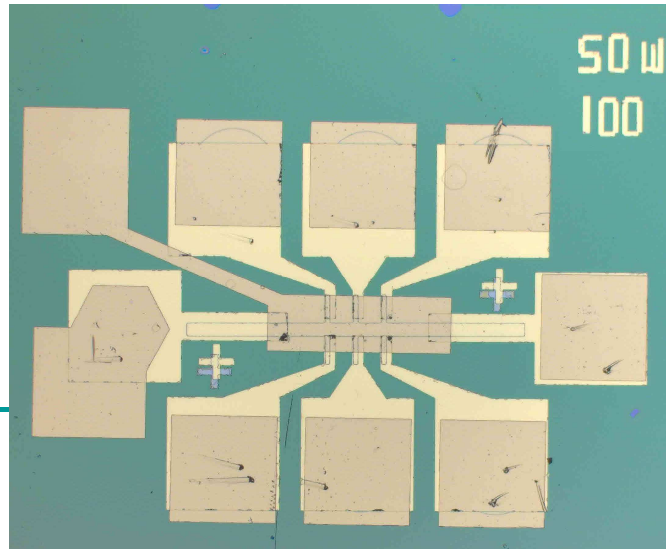


PECVD : deposit 300nm Si_3N_4

Lithography/RIE : Pattern/etch holes to Hall bar contacts

Lithography : Pattern top contacts and V gate

e- beam evaporator : Deposit Ti/Au



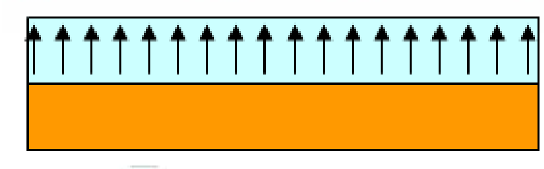
Gating QDs: Electron Beam Lithography

Outline

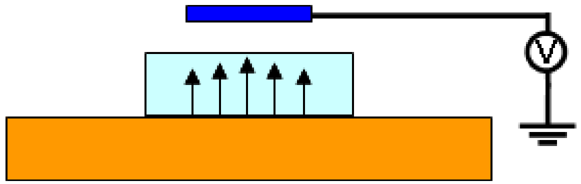
- Motivation and Background
- Our DMS: GeMn
- Hall Bars
- Summary / Future Work

Magnetic Quantum Dots in GeMn

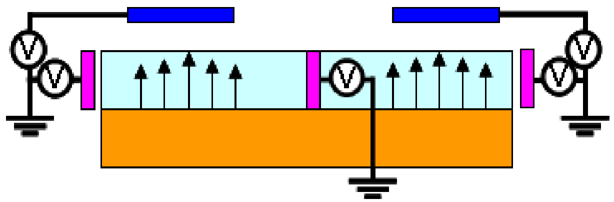
- Grow Ge QDs (Jerry Floro group)
- Use FIB to implant QDs with Mn

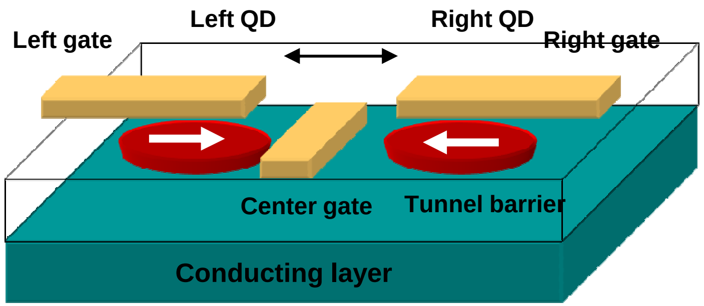


- Gate QDs – Use electric fields to modify magnetism through control of carrier concentration in the QD



- Add side gates – control interactions between neighboring QDs





Magnetic Exchange Switch with 2 MnGe QDs

Summary

- We hope to use the DMS GeMn to create a device which can be used in future logic/memory applications
- Understanding the magnetism in GeMn
  - Effects of Mn concentration, annealing on magnetism
  - AHE data mimics M vs. H data
  - PLM:
    - Suspect Mn diffusion to surface, leaving behind some substitutional Mn
    - More crystalline, less Mn clusters (clusters may give strongest FM signal)
- Electrical modification of the magnetism in GeMn
  - Preliminary results do show effect on magnetism due to Vgate

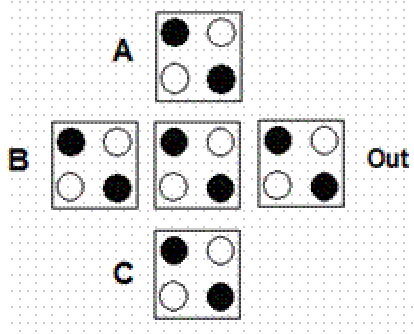
Future Work

- Gated Hall bars
- PLM with different Mn concentrations, post-anneal conditions
- Hall effect in MBE grown samples

THANKS!

QCA Logic

- Majority Gate
  - AND : 1 input fixed as “0”
    - Both remaining inputs must be “1” in order to get output of “1”
  - OR : 1 input fixed as “1”
    - Either of the other 2 inputs must be a “1” in order to get output of “1”



Majority

A	B	C	OUT
0	0	0	0
0	0	1	0
0	1	0	0
0	1	1	1
1	0	0	0
1	0	1	1
1	1	0	1
1	1	1	1

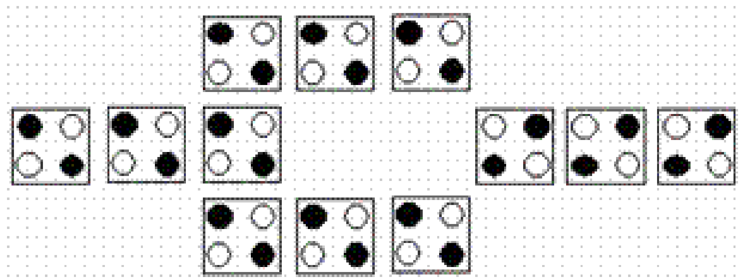
AND (Input A fixed)

A	B	C	OUT
0	0	0	0
0	0	1	0
0	1	0	0
0	1	1	1

OR (Input A fixed)

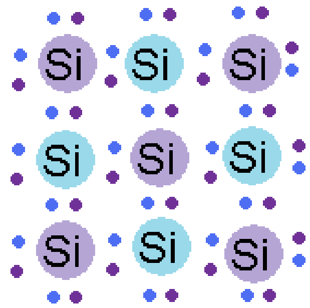
A	B	C	OUT
1	0	0	0
1	0	1	1
1	1	0	1
1	1	1	1

- Inverter
  - Only needs 1 input

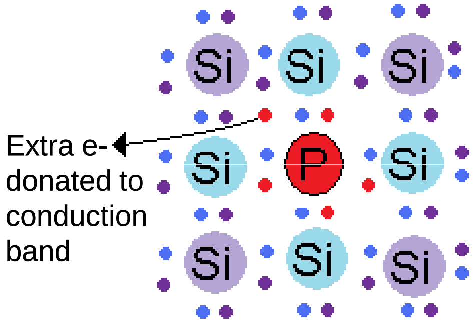


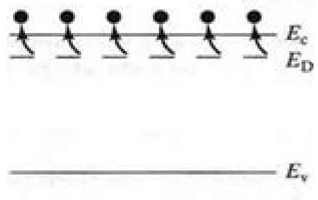
Doping a Semiconductor

- Si atom has 4 valence e–'s
  - Nearest neighbors help form covalent pairs

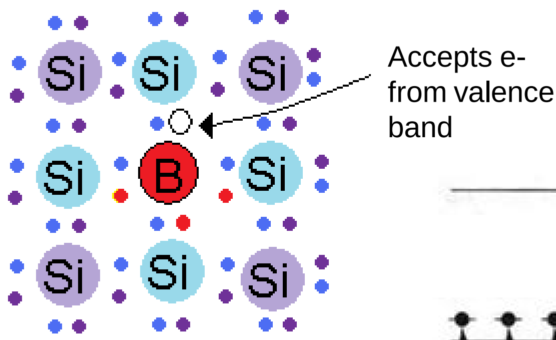


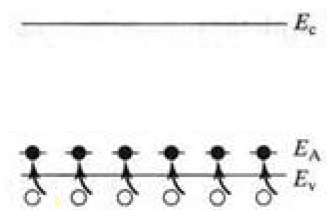
- P atom has 5 valence e–'s
  - Extra e– "donated" to conduction band ⟶ *n–type*





- B atom has 3 valence e–'s
  - Can "accept" an e– from valence band, leaving behind a hole ⟶ *p–type*

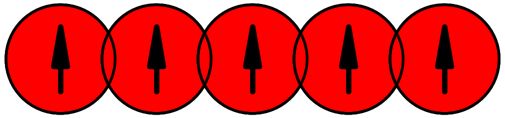




Physics of Magnetism 101

Three types of magnetic interactions

Direct exchange



Wavefunctions overlap directly

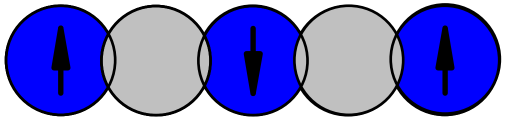
Electrons on different atoms

Antiparallel alignment favored (e.g. H_2 molecule)

Electrons on same atom

Parallel alignment favored (Hund's First Rule)

Superexchange

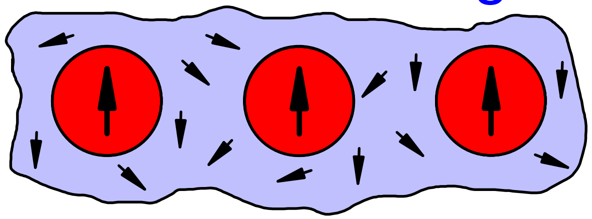


Wavefunctions interact via nonmagnetic neighbors

Electrons on different atoms

Antiparallel alignment favored (e.g. MnO, MnGe)

Indirect exchange



Wavefunctions interact via conduction electrons

Electrons on different atoms

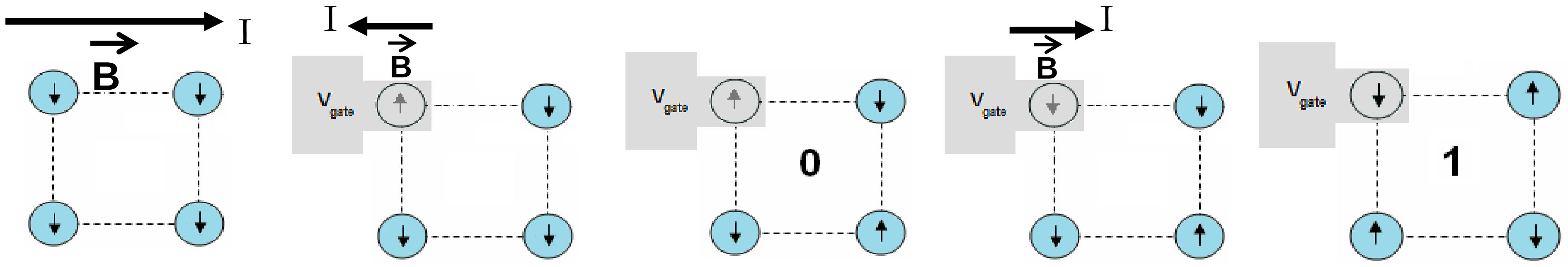
Parallel <u>or</u> antiparallel alignment favored (RKKY)

Ferromagnetic semiconductors

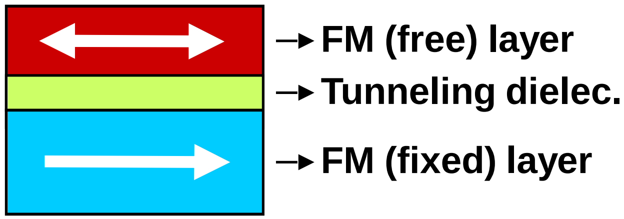
Wavefunctions interact via valence holes

Parallel alignment favored

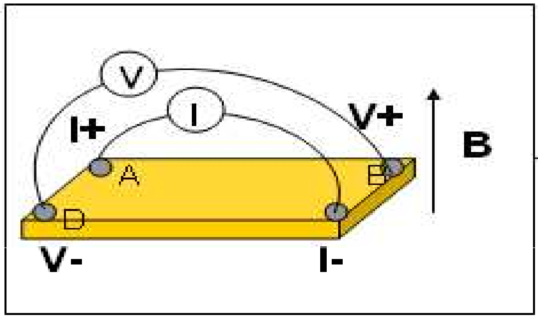
MQCA

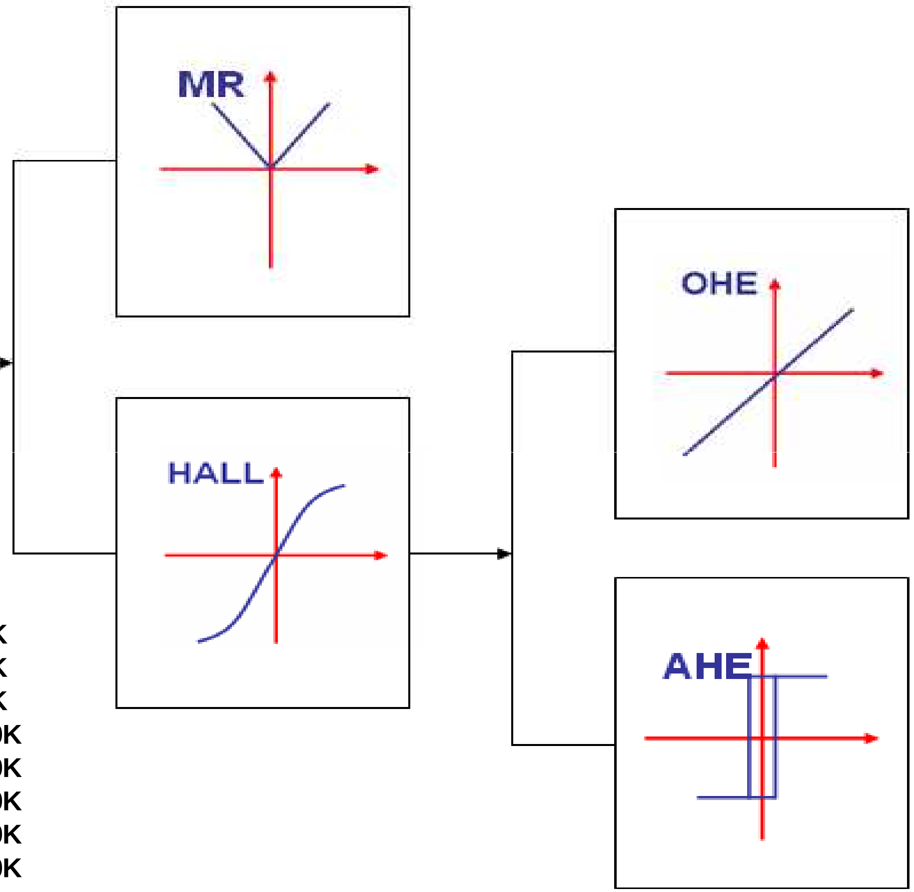


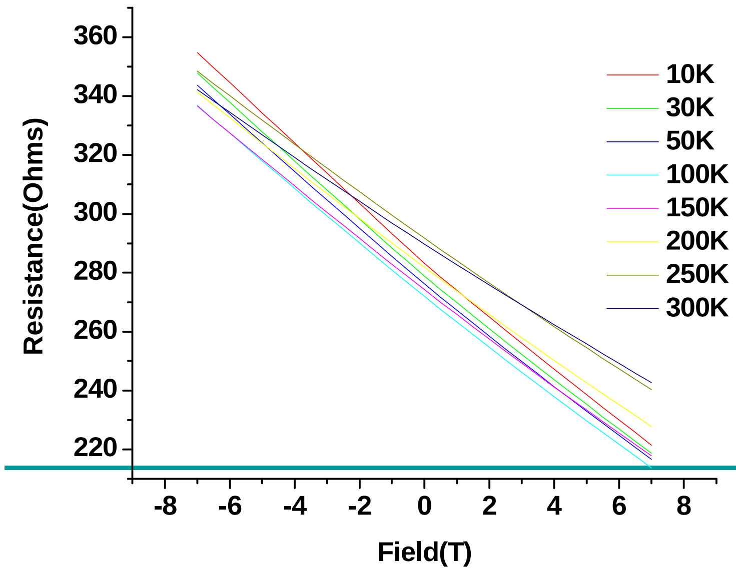
- Read－out:　Magnetic Tunnel Juntion
  - Free layer magnetized by external field
  - Applying small bias voltage creates tunneling current thru dielectric
  - Switch direction of free layer, remeasure current
  - Relative size of current gives state of fixed layer (larger current → parallel orientations)



Hall measurement data analysis procedure







$$\rho_{Hall}(H) = R_0(H)\mu_0 H + R_s(H)\mu_0 M$$

DMS – format below into bullets, add to previous slide

- These materials exhibit a spin-dependent coupling between localized states and those in the valence and conduction bands. It is due to this coupling that the holes in dilute magnetic semiconductors mediate a ferromagnetic interaction between the localized spins. This property means that it is possible to control magnetization by an electric field, which affects the carrier density in semiconductors.
- These mixed crystals (semiconductor alloys) may be considered as containing two interacting subsystems. The first of these is the system of delocalised conduction and valence band electrons. The second is the random, diluted system of localised magnetic moments associated with the magnetic atoms. The fact that both the structure and the electronic properties of the host crystals are well known means that they are perfect for studying the basic mechanisms of the magnetic ineractions coupling the spins of the band cariers and the localised spins of magnetic ions. The coupling between the localised moments results in the existence of different magnetic phases (such as paramagnets, spin glasses and antiferromagnets).

Questions

- (11) How does a spin couple to a hole?
  - – hole has opposite spin as e–
- (11) RKKY model?
  - – not needed
- (13) Coercive field?
- (14) Magnetic field in first 3 pics?
  - – no
- (25) AMR?
  - – remove
- (27) explanation of $AMR (3rd bullet)
  - – remove

- Possible scenarios:
  - More crystalline, more Mn is diffused out thru surface
  - More crystalline, less Mn clusters (clusters may give strongest FM signal)
- Continue experiments with bigger pieces, more Mn implanted, different post-anneal conditions