Graduate School of Pure & Applied Sciences, University of Tsukuba

Kuroda Laboratory

Semiconductor Spintronics Laboratory

○ Semiconductor Spintronics

●Semiconductor Electronics

Ex. Transistor, CPU, DRAM, LED

Utilize ***charge*** of electrons

☺ High Speed (calculation)

☹ Volatility

→ We need much electric power to keep data.

●Magnetic Engineering

Ex. Magnet, HDD, MO,

Utilize *spin* of electrons

☺ Non-Volatility (storage)

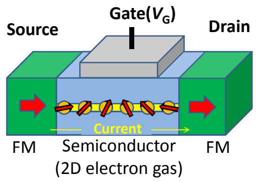
☹ Low Speed

Spintronics : Utilize both of charge and spin of electrons

Ex. Giant Magnetic Resistivity effect (GMR) ⟶ Nobel prize in 2007

●Future application of Semiconductor Spintronics

Ex. Spin transistor



V_G is used to control spin direction of carrier.

At the interface between semiconductor and Drain, Spin directions between the carrier and Drain FM are

Parallel ⟶ large current

Anti-parallel ⟶ small current

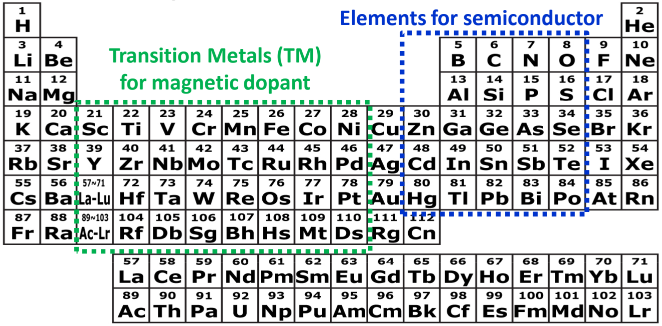
We can control current with low power.

Other possible applications

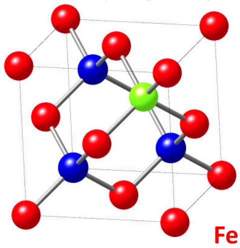
- High-speed high-density nonvolatile memory
- Reconfigurable logic devices/computing
  - ⟶ Realization of no standby-power electricity
- Integrated magneto-optical devices
- Quantum information devices using spin states

In order to realize spintronics devices, we should explore ferromagnetic materials for injection and detection of a spin polarized current into a semiconductor.

○ Diluted Magnetic Semiconductors (DMS)



Doping magnetic TM in a host semiconductor material



TM ions substitute atomic sites of a host semiconductor.

⟶ **Diluted Magnetic Semiconductors (DMS)**

●Characters of DMSs

- They have both properties of the host semiconductor and doped TM ions (magnetic) .
- They can grow epitaxially on a semiconductor surface.

Ferromagnetic DMS @ Room temperature

Promising materials for semiconductor spintronics

Search for high-T_C ferromagnetic semiconductors

GaN + Mn T_C ~ **900K** (Sonoda) **vs** **PM** (Munekata)
+ Cr **> RT** (Asahi)
+ Gd **> RT** (Asahi, Ploog)ZnO
ZnO + Co T_C **> RT** (Tabata) **vs** **PM** (Kawasaki)
TiO_2 + Co T_C **> RT** (Kawasaki)
ZnTe + Cr T_C ~ **300K** (Saito)
Ge + Mn T_C ~ **120K** (Park)
+ Fe **170K** (Tanaka)

- Origin of FM
  Intrinsic of DMS
  or
  Extrinsic by precipitate (ex. TM cluster) ?
- Mechanism ?

Wide variety of magnetism reported so far even for the same materials

Possible factors which may explain these contradictory results of magnetic properties

- **Extrinsic precipitates of FM compounds with different phases**
- **Non-uniformity of magnetic impurities in the host crystal**

We must fabricate DMS samples precisely.

○ How to Fabricate DMS

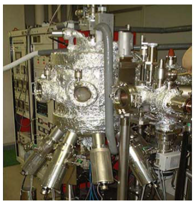
→ Molecular Beam Epitaxy (MBE)

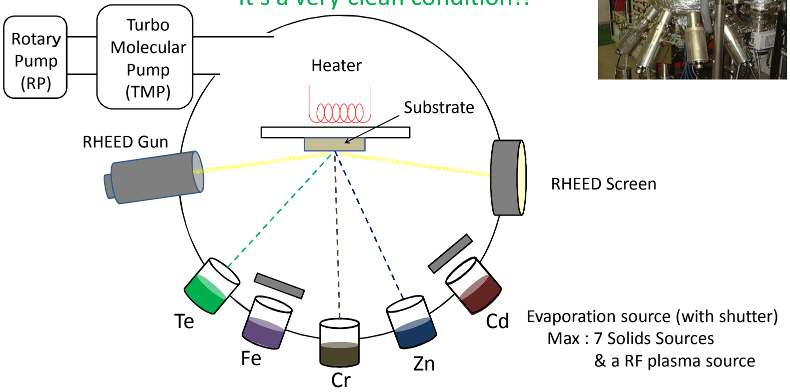
Schematic image of MBE growth chamber

Inside of the chamber is Ultra High Vacuum condition.

~10^{-10} Torr (ex. 1 atm = 760 Torr)

It's a very clean condition!!





Evaporation source (with shutter)
Max : 7 Solids Sources
& a RF plasma source

Merits of MBE growth

- Keeping a clean substrate surface for many hours
- Precise control of growth condition
  - Substrate temperature
  - Thickness of growth films (~1 Å/ s)
  - Flux ratio ⟶Composition of dopant atom (< 1 %)
- Growth films in non-thermal equilibrium condition
- Characterize a sample surface structure during growth by Reflection high-energy electron diffraction (RHEED)

○ Highlights of Our Recent Results

Physical Review Letters **97**, 037201 (2006) , Nature Materials **6**, 440 (2007)

Ferromagnetic properties of (Zn,Cr)Te with Acceptor & Donor doping

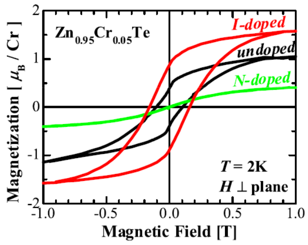
⟶ Intrinsic Room-temperature Ferromagnetism when Cr composition is 20 %.

●Doping of charge impurities

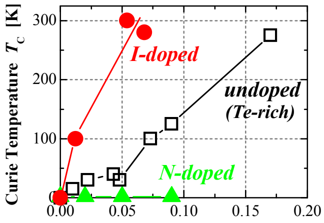
***p*-type (Acceptor) : Nitrogen (N)** ***n*-type (Donor) : Iodine (I)**

Magnetic properties (SQUID)

M-H curves



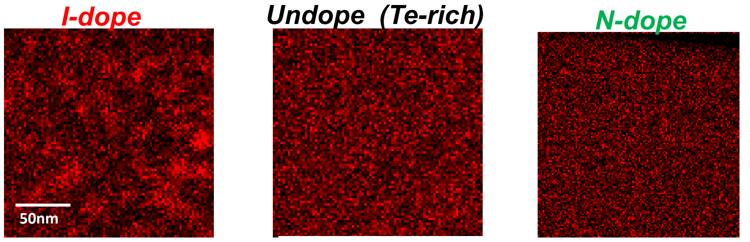
T_c at various Cr composition



I-doping* Ferromagnetism is *enhanced

N-doping* Ferromagnetism is *suppressed

Spatial distribution properties of Cr atoms (TEM)



Inhomogeneous ⟵ ***Cr distribution*** ⟶ ***Homogeneous***

Attractive ⟵ ***Interaction between Cr*** ⟶ ***Repulsive***

Enhanced ⟵ ***Ferromagnetism*** ⟶ ***Suppressed***

Summary

Doping of charge impurities or deviation from stoichiometry

⟶ **Tune *the interaction* between TM ions**

⟶ **Control *cluster formation & magnetic properties***