FERROMAGNETIC SEMICONDUCTORS FOR SPINTRONIC AND MAGNETOELECTRONIC DEVICES

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Introduction and Overview

- Moore's Law of microelectronics
  - Reaching the scale-down limit
- Suggestions for future:
  - Bottom-up approach to fabrication
  - Integration of function in devices
  - Change in characteristics of information carrier
  - Bioelectronics, polymer electronics, molecular electronics, spintronics

What is spintronics?

- Currently: Processing by charge, storage by spin, coding and transmission using photons
- Spintronics →Information Storage + Processing
- Spin: additional degree of freedom
- Mott: Spin-polarized currents in ferromagnetic metals
- 10X difference between majority and minority-spin carrier currents in Fe and Co, because:
  - Splitting into majority and minority spin bands
  - Spin-dependent cross-section of impurities
- Ferromagnetic proximity effect

Spintronic devices

- First spintronic device: spin valve based on GMR (1988)
- Requirements for spintronics:
  - Efficient electrical injection of spin-polarized carriers
  - Efficient transmission during transport of carriers through semiconductor
  - Capability to detect or collect spin-polarized carriers
  - Control and manipulation of transport via external means (e.g. biasing of a gate contact on a transistor)

Materials with a spin!

- Ferromagnetic semiconductors
  - Combined semiconducting and magnetic properties for multiple functionalities
  - Easy growth of ferromagnet-semiconductor nanostructures
  - Easy spin injection: e.g. spin transistor
- Half-metallic ferromagnets: 100% spin polarization
  - Two spin channels: one metallic, other with gap at fermi level
  - Examples: Extreme substitution of V, Cr and Mn into GaAs, InAs, GaSb, InSb, GaP and InP

Introduction to ferromagnetic semiconductors

- 1970s: Eu and Cr chalcogenides
  - Rock salt type EuO and EuS
  - Spinel type $CdCr_2S_4$ and $CdCr_2Se_4$
- Diluted magnetic semiconductors
  - Spins from 3d or 4f e^-s of transition metal
  - Examples: $Cd_{1-x}Co_xSe$, $Ga_{1-x}Mn_xAs$ and Si:Er
  - II-VI compounds: tough to get a good number of mobile carriers by doping
  - GaMnAs: canonical DMS; T_c = 30-170 K
  - InMnAs: T_c=35 K
  - Theoretical prediction of T_c>R.T. realized in Mn-doped ZnO and GaN, and in Co-doped TiO_2 and ZnO
  - Manganites & Mn-doped IV semiconductors

Theory of Magnetism in ferromagnetic semiconductors

- Zener model for ferromagnetism
  - Ferromagnetic metals: Parallel coupling between localized spins (Heisenberg Exchange)
  - Quantum-mechanical treatment (RKKY):
    - Sign of interaction depends on distance between localized spins
    - Indirect exchange mechanism via charge carriers
  - DMS: Holes mediate between ferromagnetically coupled spins
    - Mn-doped III-V compounds: holes due to Mn
    - Mn-diluted II-VI compounds: doped with N

Applicability of the Zener Model

- Apply to wide-band gap semiconductors:
  - Short bond lengths => strong coupling between holes (anions) & spins (cations) => Large spontaneous moment
  - Many: T_c> R.T. but much lower moment than predicted
- Fails when substitution exceeds solubility limit:
  - Ferrimagnetic or ferromagnetic precipitates => unaccounted magnetism !

Processing of ferromagnetic semiconductors

- 1970s: II-VI by variant of Bridgeman =>spin disorder or AF coupling
- Non-equilibrium processing
  - MBE for low-T growth of Mn-doped III-V
    - (For single phase material at high Mn-doping, which is not possible at equilibrium)
  - PLD for oxides (doped ZnO, SnO, TiO_2)

Characterization Techniques: Spin Manipulation

- GaMnAs: holes contribute to magnetism; so processes that change carrier concentration can be used for spin manipulation
  - Femtosecond laser pulses

    Spin alignment in polarized light; but precession leads to breakup; however fast laser pulses can maintain spin coherence
  - Electrical spin injection

    Quantum well structure with P-type ferromagnetic semiconductor on non-magnetic semiconductor: holes injected are spin-polarized => polarized light

Characterization Techniques (Contd.)

- Magneto-transport of charge carriers
  - Hall Effect

    Anomalous Hall effect due to spin-orbit coupling; electrical means of establishing weak magnetism in magnetic semiconductors

  - Magnetoresistance

    Additional term in Kohlers rule from spontaneous MR (AMR):

    $$\Delta\rho/\rho = a\,(H/\rho)^2 + b\,(M/\rho)^2$$

    Functional dependence of AMR:

    $$\Delta\rho(H)/\rho_{av} = \Delta\rho/\rho_{av}\,(\cos^2\theta - 1/3)$$

Example of a Hall effect measurement

Image removed due to copyright considerations. See reference below.

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Hall Resistivity versus applied field for $Ti_{1-x}Co_xO_{2-\delta}$ (The captions represent electron densities) [H. Toyosaki, T. Fukumura, et.al., Nature Materials Vol. 3 (2004)]

Potential Applications

Spin valves and GMR devices

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Applications: Magnetic field sensors, read heads, galvanic isolators and magnetic random access memory

[S.A. Wolf, D.D.Awschalom, et. al. Science, Vol. 294., 1488 (2001)]

Magnetic Tunnel Junctions

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Non-volatile memory applications, instant turn-on computers

[S.A. Wolf, D.D.Awschalom, et. al. Science, Vol. 294., 1488 (2001)]

- Spin LEDs
  - Spin polarized charge carriers → Polarized light
  - No need for polarizing filters → Increase of efficiency
- Spin FETs
  - Source and drain from ferromagnetic metals
  - Channel from semiconducting material
  - Additional gating action via magnetic field
  - Non-volatile memory due to spin polarization
  - Conductivity mismatch minimized by use of ferromagnetic semiconductor

THANK YOU !