Magic triangle

Magic triangle

Materials science

epitaxy, self organized growth
organic synthesis
implantation, isotope purification
atom and molecule manipulation
nanolithography, nanoprinting
beam and scanning probes
....

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Physics of complex systems

- exotic ground states and quasiparticles
- phase and statistical transformations
- complex dynamics
- ....

Magic triangle

Materials science

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Physics of complex systems

exotic ground states and
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phase and statistical
transformations
complex dynamics
....

High tech/IT

photonics (optoelectronics)
MEMS, NEMS
electronics, magnetoelectronics
spintronics ....

SEMICONDUCTOR SPINTRONICS

Tomasz DIETL

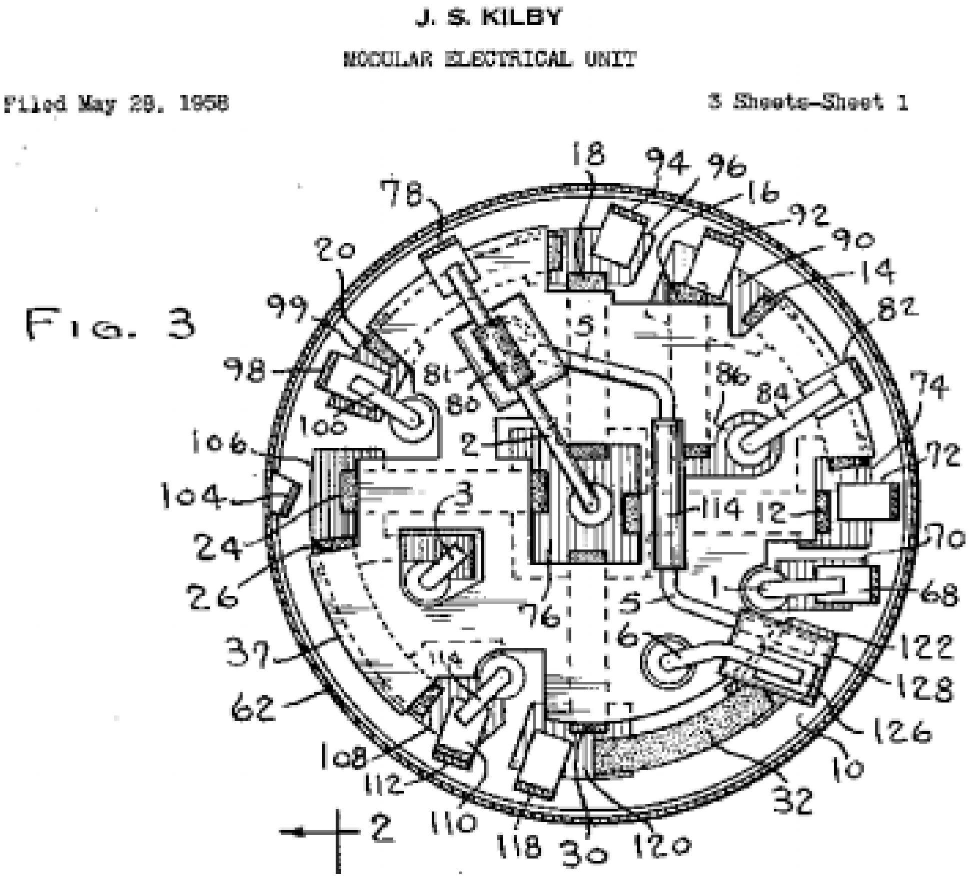
Institute of Physics, Polish Academy of Sciences, Warsaw

- **Why spin electronics?**
  - -- **semiconductors**
  - -- **ferromagnetic metals**

2. **Ferromagnetic semiconductors**
3. **Spin manipulation**
   - -- **magnetization**
   - -- **single spins**

reviews: listed in the abstract

Integrated circuits

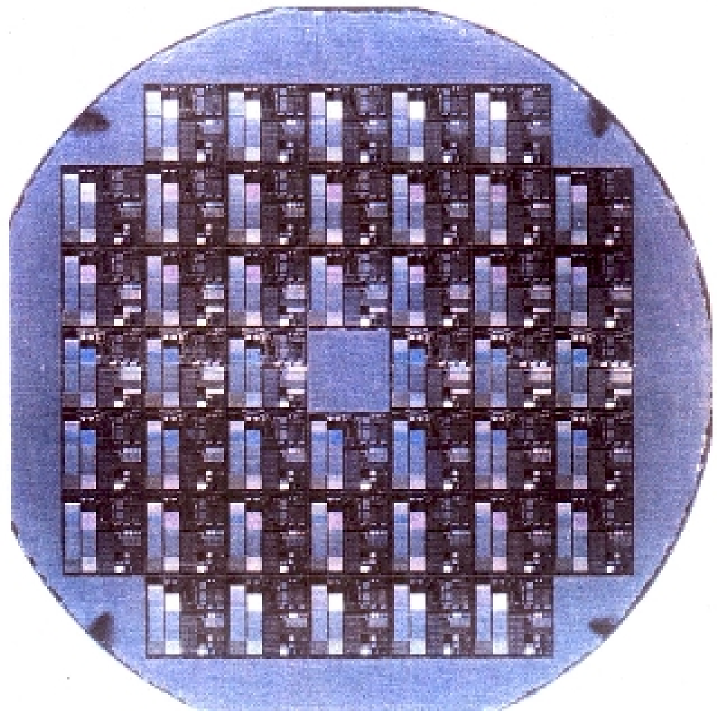


4 transistors

J. S. Kilby

US Patent Office, 3 052 822

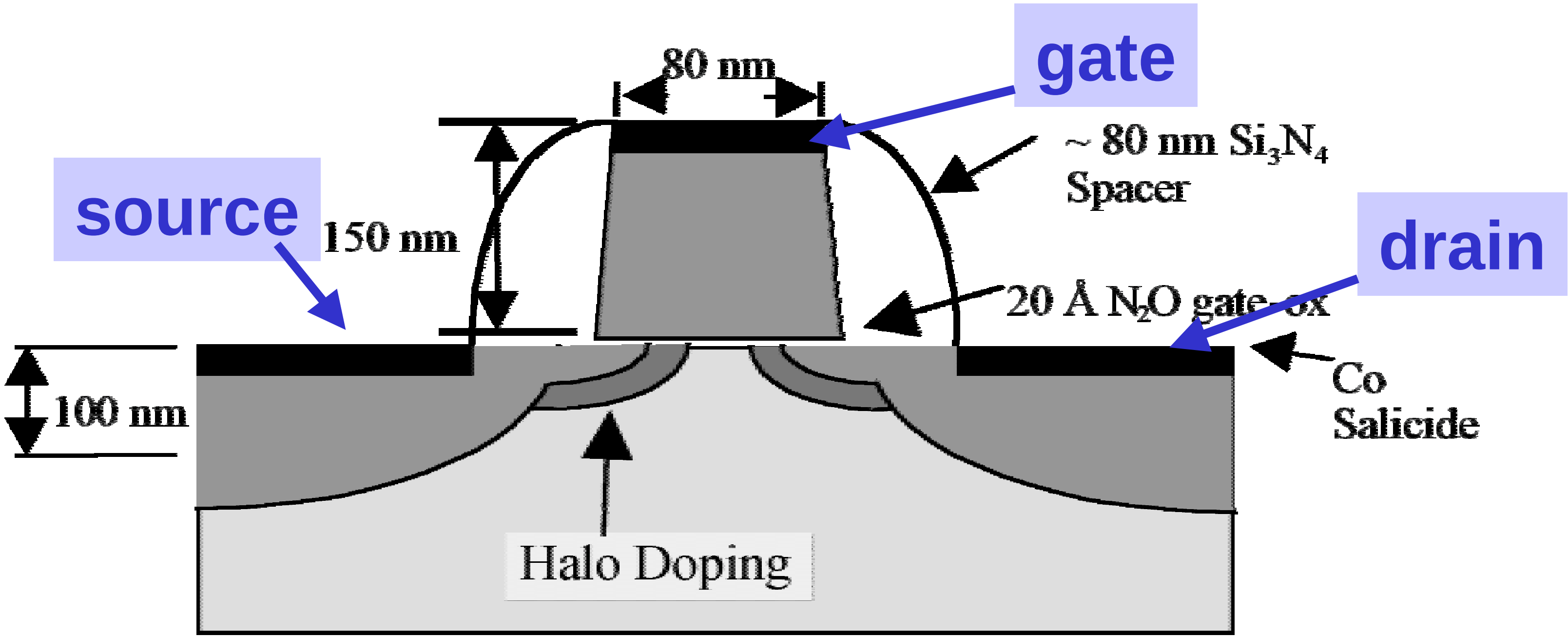
2002



10^9 transistors

processing and dynamic storage of information ; μP i DRAM

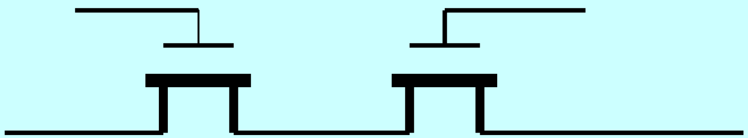
Field effect transistor
Si-MOS-FET



MOSFET – resistor + capacitor

Two states: conducting/non-conducting

eg. multiplication (AND)



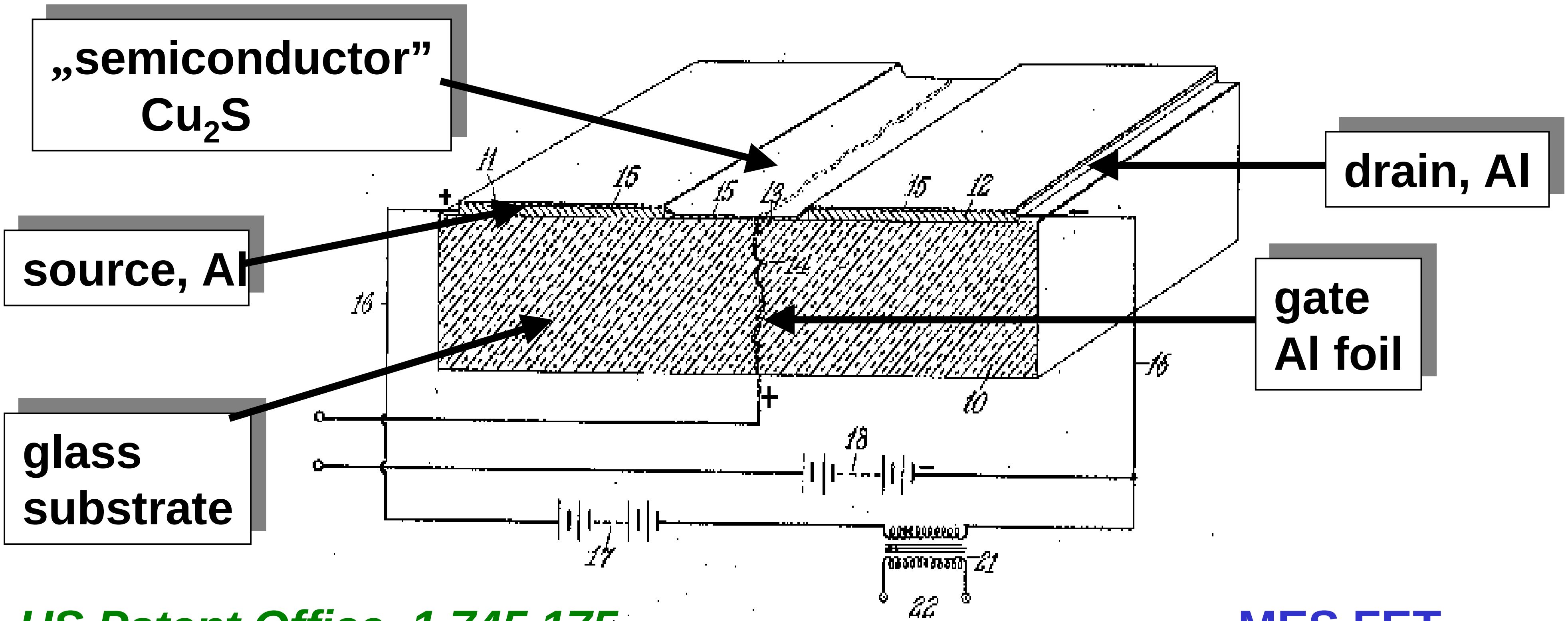
JULIUS EDGAR LILIENFELD, OF BROOKLYN, NEW YORK

METHOD AND APPARATUS FOR CONTROLLING ELECTRIC CURRENTS

Application filed October 8, 1926, Serial No. 140,363, and in Canada October 22, 1925.

I claim :—

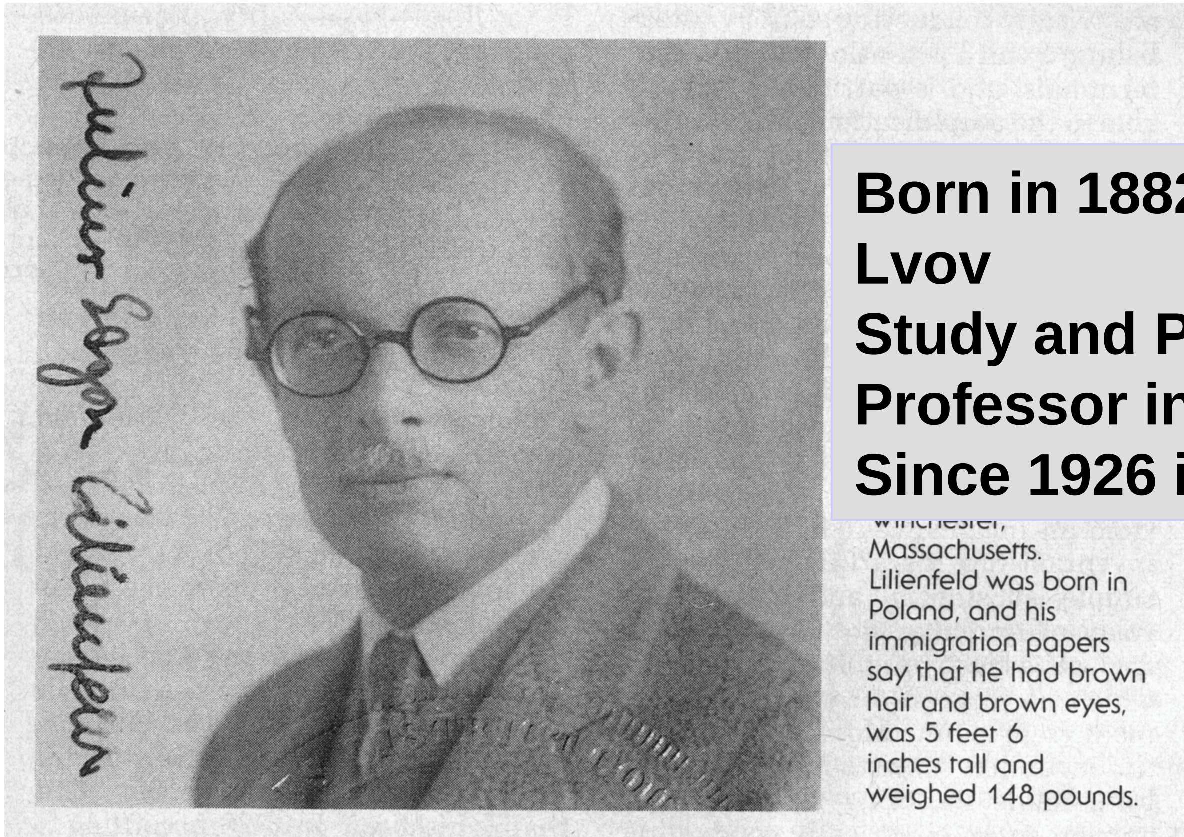
1. The method of controlling the flow of an electric current in an electrically conducting medium of minute thickness, which comprises subjecting the same to an electrostatic influence to impede the flow of said current



US Patent Office, 1 745 175

MES FET

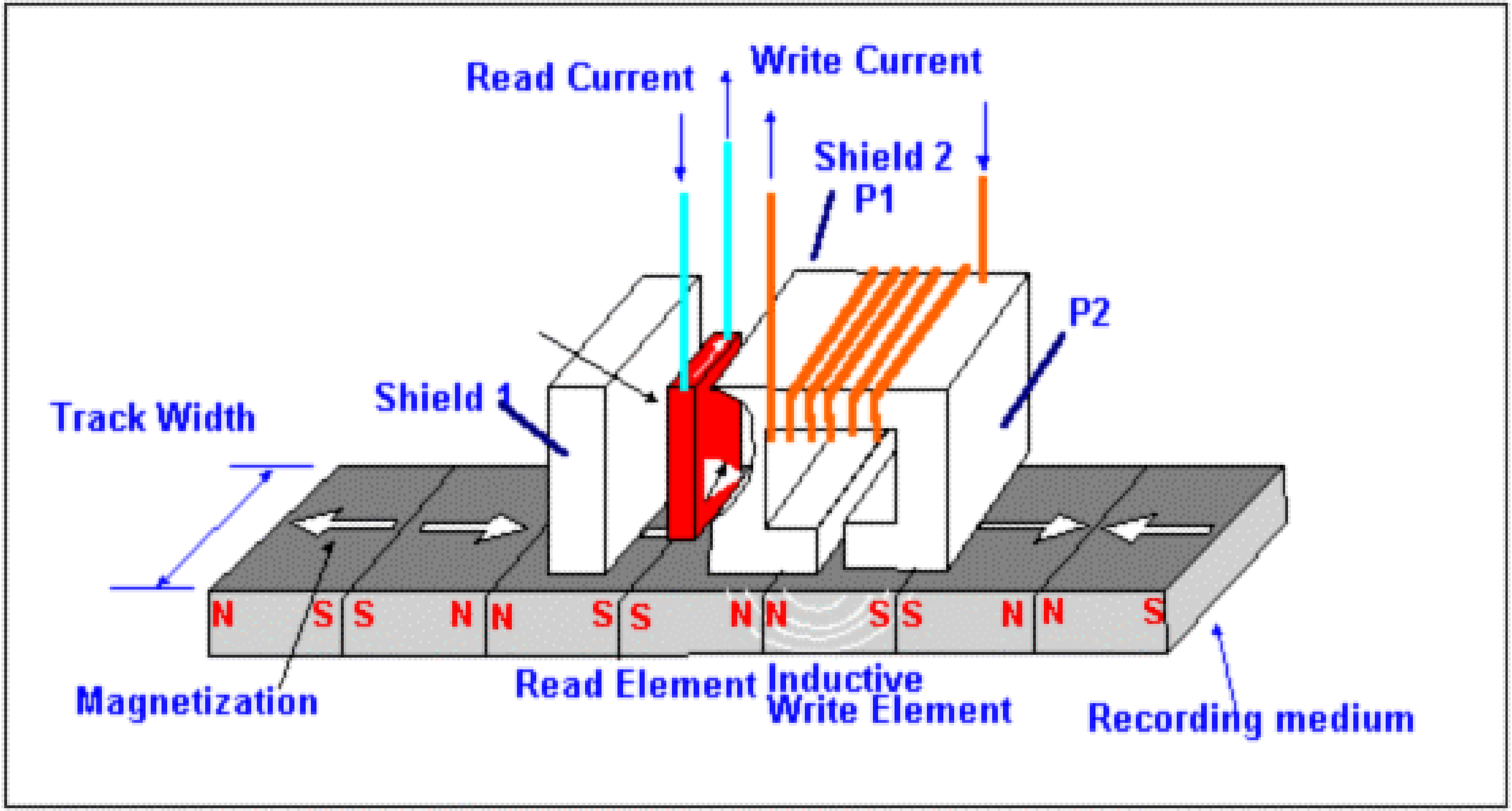
Julius Edgar Lilienfeld (1882-1963)



Born in 1882 and till 1899 in Lvov
Study and PhD (1905) in Berlin
Professor in Leipzig (1910-26)
Since 1926 in USA

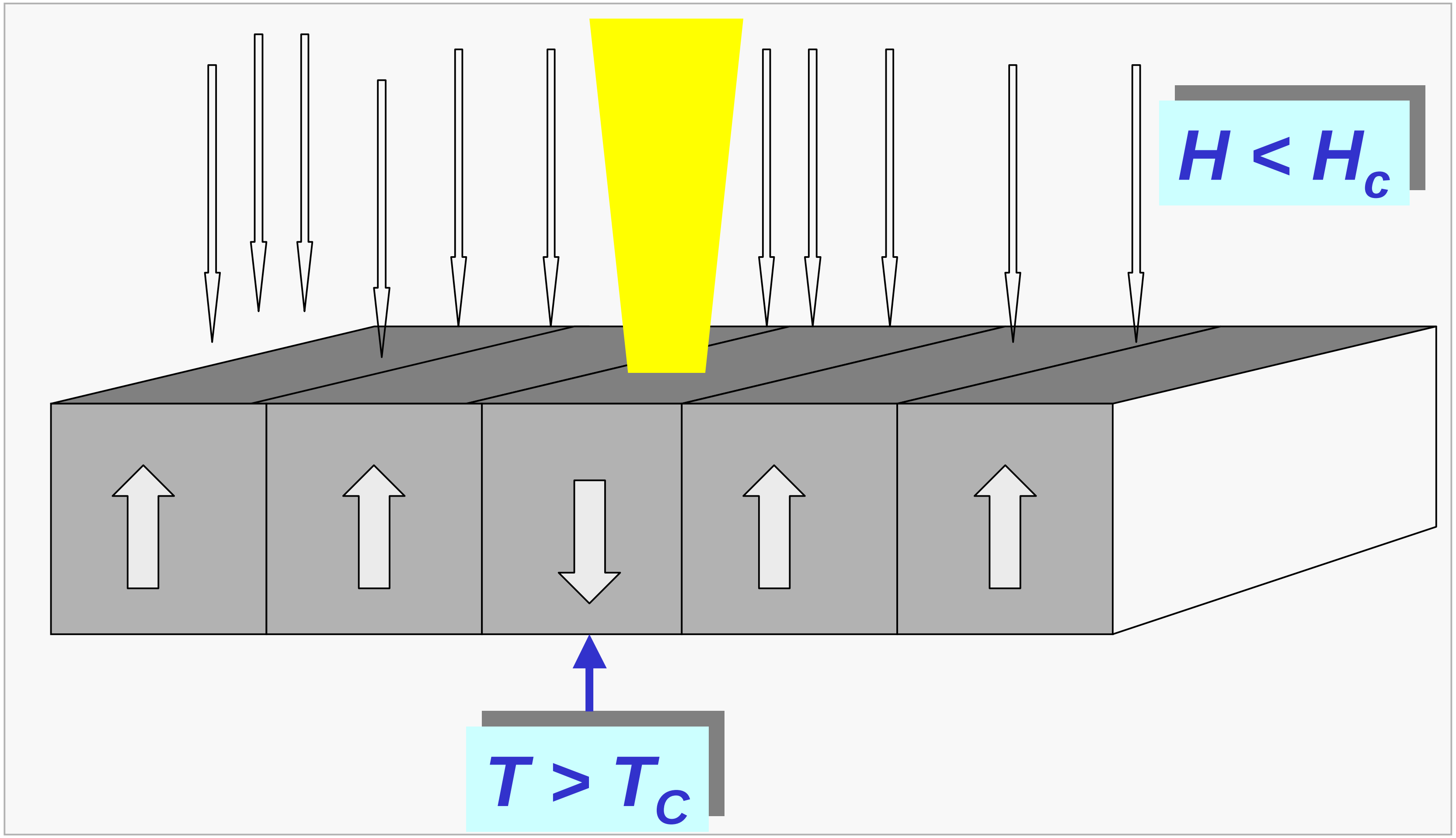
Kleint, *Prog. Surf. Sci*. '98

Storing of information on hard disk



- **high density and non-volatile (5GB/cm^2)**
- **slow access and non-reliable** (moving parts)

Storing of information on magnetooptical disc



- writing: heating above T_C
- reading: Kerr effect

Barriers

- **financial, legal, psychological, ...**
- **technical**

  - heat release, defects in oxide, ...
- **physical**

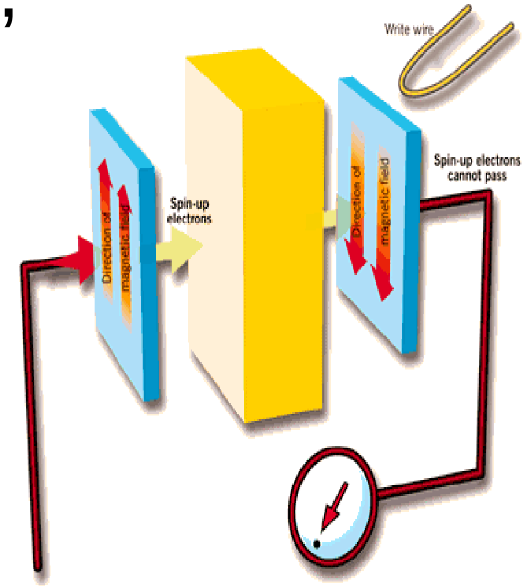
  - grain structure of matter: Coulomb blockade, ...
  - quantum phenomena: interference, tunneling, ...
  - thermodynamic phenomena: superparamagnetism, ...

Driving forces

- **entertainment industry**
- **...**

➔ nanotechnology

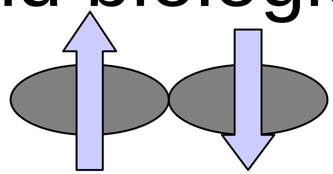
- New information carrier
  - electron → photon, flux (SQUID loops), vortex (type II superconductors);
  - spin rather than charge ...



- New principle of device operation

  quantum devices, spin transistors,

- New architecture
  - physical, chemical and biological processes
  - quantum computing



- Integration of functions, not only elements

=> Spintronics

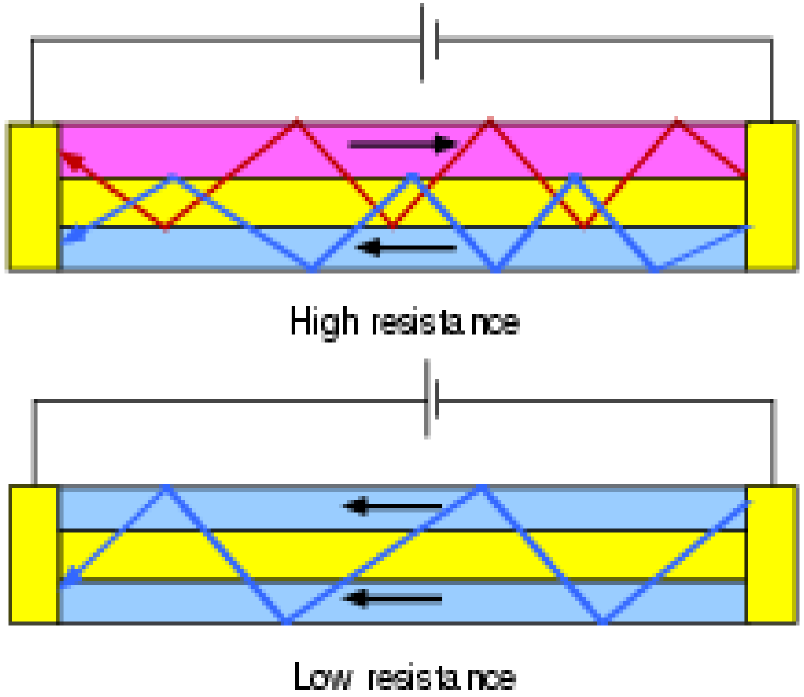
SPINTRONICS
exploiting spin, not only charge

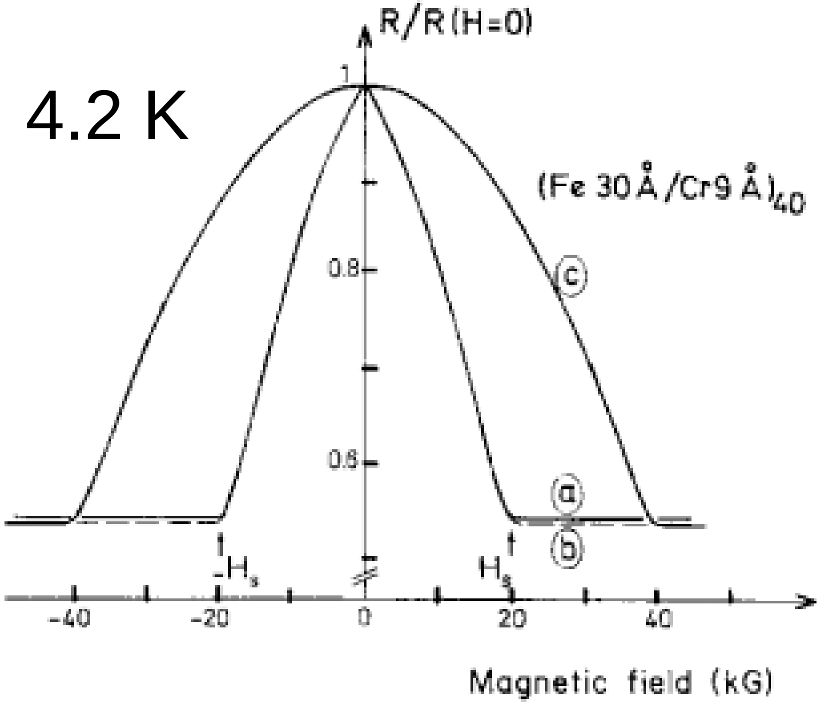
rational:

spin robust to external perturbations

- Storing *and* processing of classical information
- Storing *and* processing of quantum information
- Sensing magnetic field

Giant magnetoresistance (GMR) in ferromagnetic metal multilayers



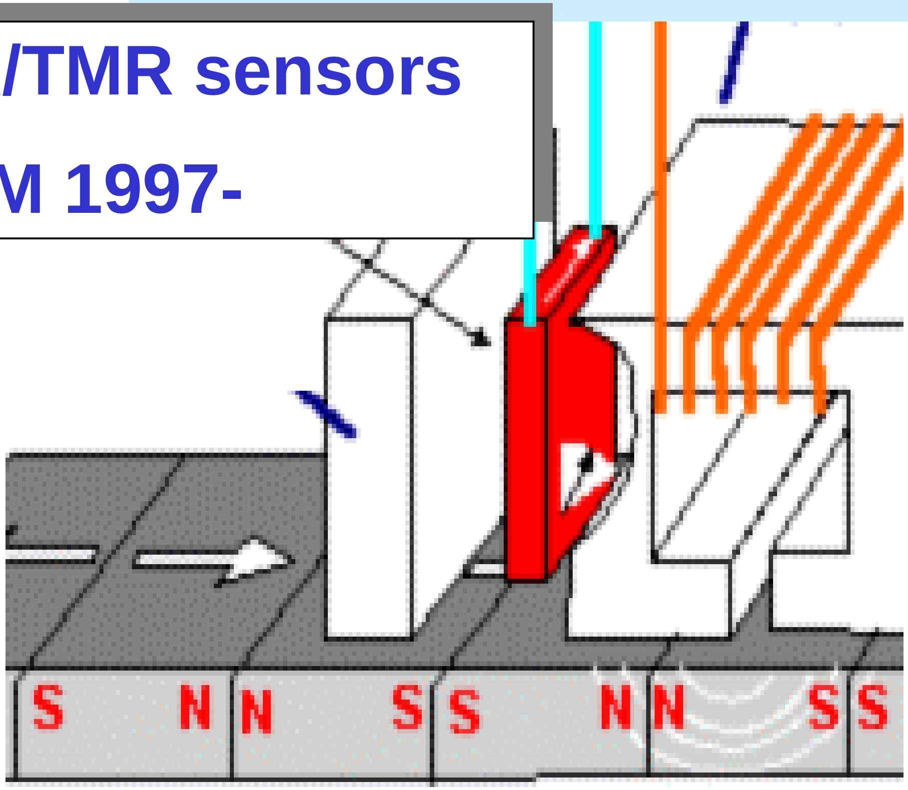


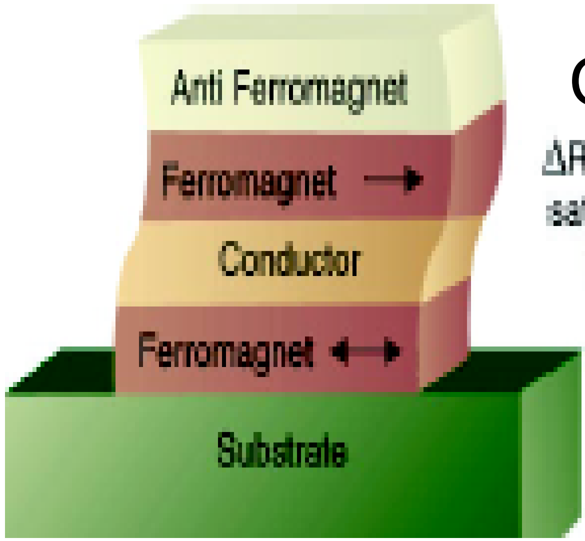
A. Fert et al., P. Gruenberg et al., S. Parkin et al., 1988-91
J. Barnaś et al. (theory)

Information reading

GMR/TMR sensors

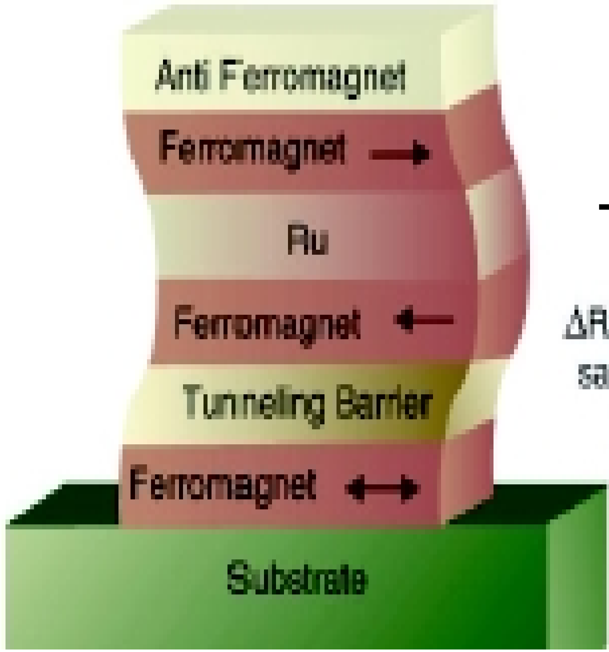
IBM 1997-





GMR

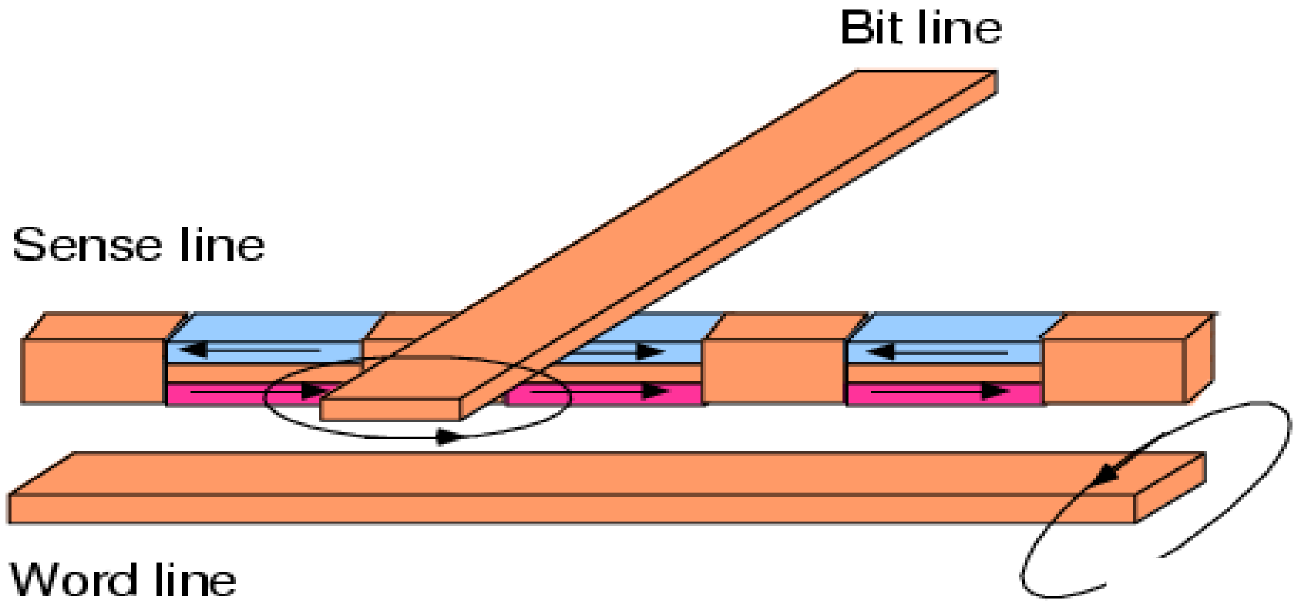
ΔR/R -5%-10%
saturation field
10-30 Oe



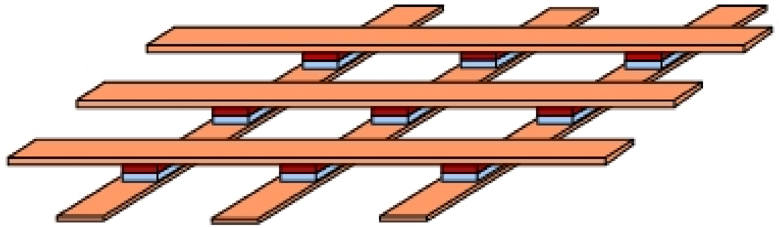
TMR

ΔR/R -20%-50%
saturation field
10-30 Oe

Magnetic random access memory (MRAM)



Infineon, Motorola, 256 kb



- non-volatile
- fast (50 ns)
- reliable
- radiation hardness
- ....

Difficulties:

- thin oxide, 1.2 nm
- large writing currents
- ...

Spintronics – material aspects

Why to do not combine complementary properties and functionalities of semiconductor and magnetic material systems?

- ***hybrid structures***

-- overlayers or inclusions of ferromagnetic metals => source of stray fields and spin-polarized carriers

-- soft ferromagnets => local field amplifiers

-- hard ferromagnets => local field generators

(cf. J. Kossut, ILC, Budapest'02)

- ***ferromagnetic semiconductors***

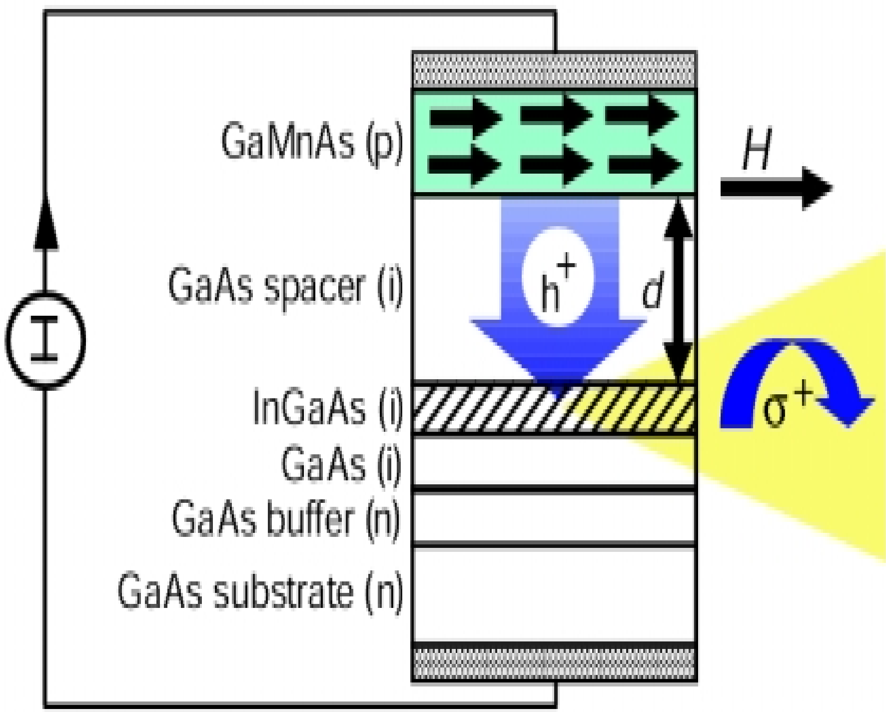
Ferromagnetic semiconductors

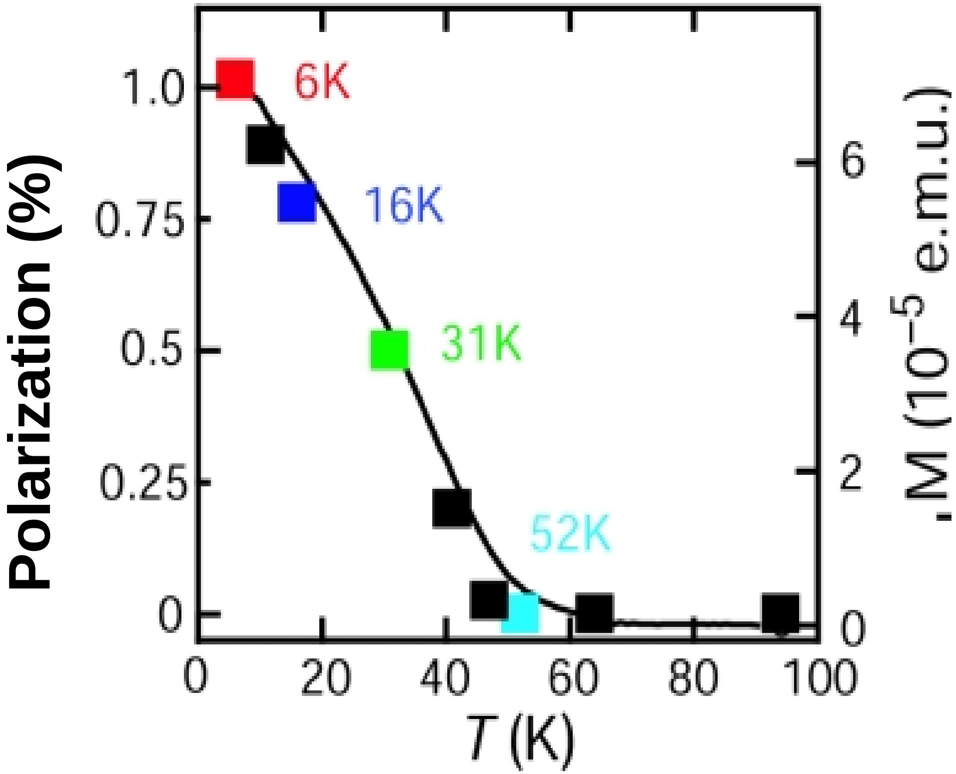
- **magnetic semiconductors**
  short-range ferromagnetic super- or double exchange
  EuS, $ZnCr_2Se_4$, $La_{1-x}Sr_xMnO_3$, ...

- **diluted magnetic semiconductors**
  long-range hole-mediated ferromagnetic exchange
  IV-VI: p-$Pb_{1-x-y}Mn_xSn_yTe$ *(Story et al.'86)*
  III-V: $In_{1-x-}Mn_xAs$ *(Munekata et al.'89,'92)*
  $Ga_{1-x-}Mn_xAs$ *(Ohno et al.'96)* **$T_C \approx 100$ K for $x = 0.05$**
  II-VI: $Cd_{1-x}Mn_xTe/Cd_{1-x-y}Zn_xMg_yTe$:N QW
  (Cibert et al.'97, Kossacki et al.'99)
  $Zn_{1-x}Mn_xTe$:N *(Ferrand et al.'99)* $Be_{1-x}Mn_xTe$:N *(Hansen et al.'01)*

III-V and II-VI DMS:
quantum nanostructures and ferromagnetism combine

Spin injection in p-i-n (Ga,Mn)As /(In,Ga)As/GaAs diode (spin-LED)





Ohno et al., Nature '99

The nature of the Mn state and its coupling to carriers

Mn: $3d^5 4s^2$

II-VI: **Mn electrically neutral ($3d^5$, S = 5/2)**
–doping by acceptors necessary

III-V: **Mn acts as source of spins and holes**

- **large *p-d* hybridization and large intra-site Hubbard *U* => Kondo hamiltonian $H = -\beta N_o \mathbf{S}\mathbf{s}$ => *large Mn-hole exchange***

-- (Ga,Mn)As: $\beta N_o \approx -1.2$ eV *(Szczytko et al., Okabayashi et al.)*
-- (Zn,Mn)Te: $\beta N_o \approx -1.0$ eV *(Twardowski et al.)*

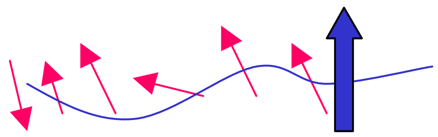
- **no s-d hybridization => small Mn-electron exchange**

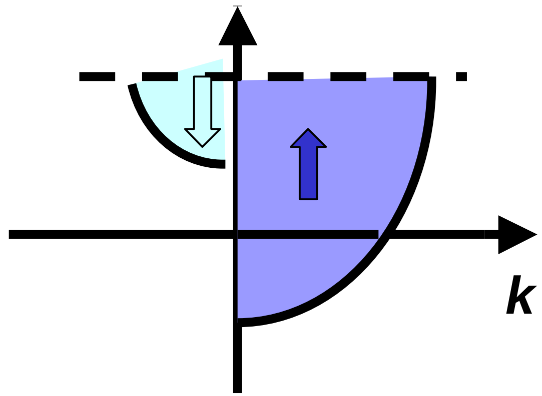
$\alpha N_o \approx 0.2$ eV (*Gaj et al.*)

Mean-field Zener model

Which form of Mn magnetization minimizes *F[**M(r)**]*?

$$F = F_{Mn}[\mathbf{M(r)}] + F_{holes}[\mathbf{M(r)}]$$





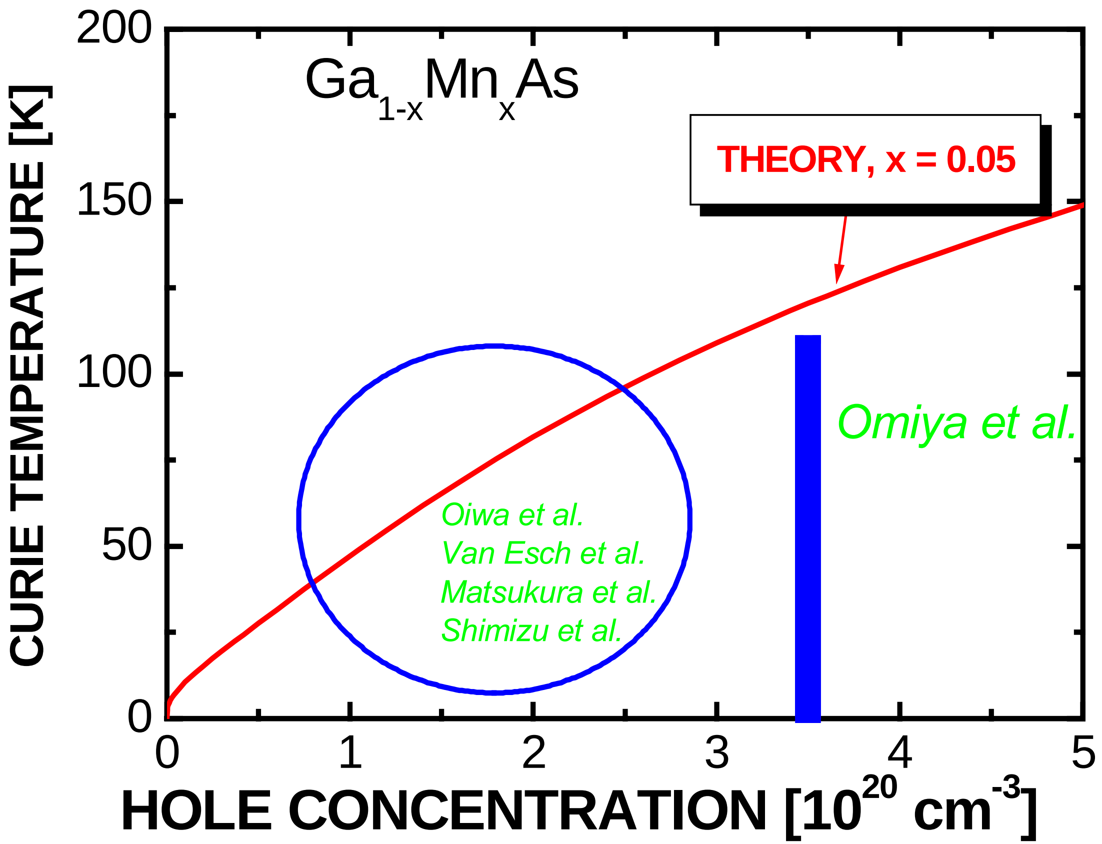
$\mathbf{M(r)} \neq 0$ for $H = 0$ at $T < T_C$

if ***M(r)*** uniform => ferromagnetic order

otherwise => modulated magnetic structure

$n_{holes} \ll N_{spins}$ ➔ **Zener ≡RKKY**

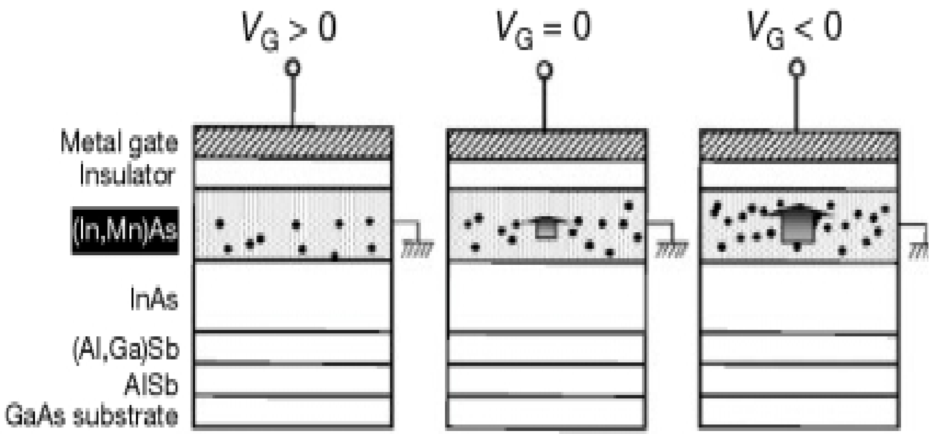
Curie temperature in p-$Ga_{1-x}Mn_xAs$
theory vs. experiment

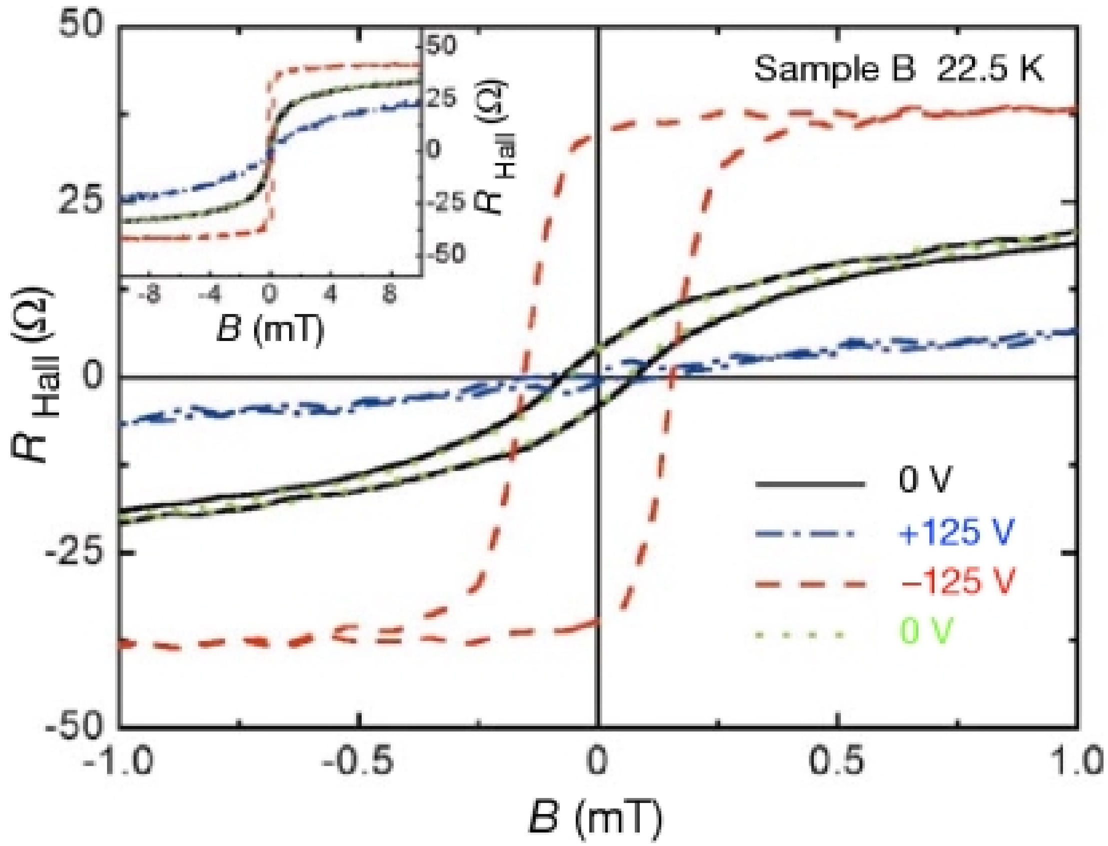


- **Anomalous Hall effect ➔ *p* uncertain**
- **Omiya et al.: 27 T, 50 mK**
- ***Theory:* T_C > 300 K for *x* > 0.1 and large *p***

T.D. et al., PRB'01

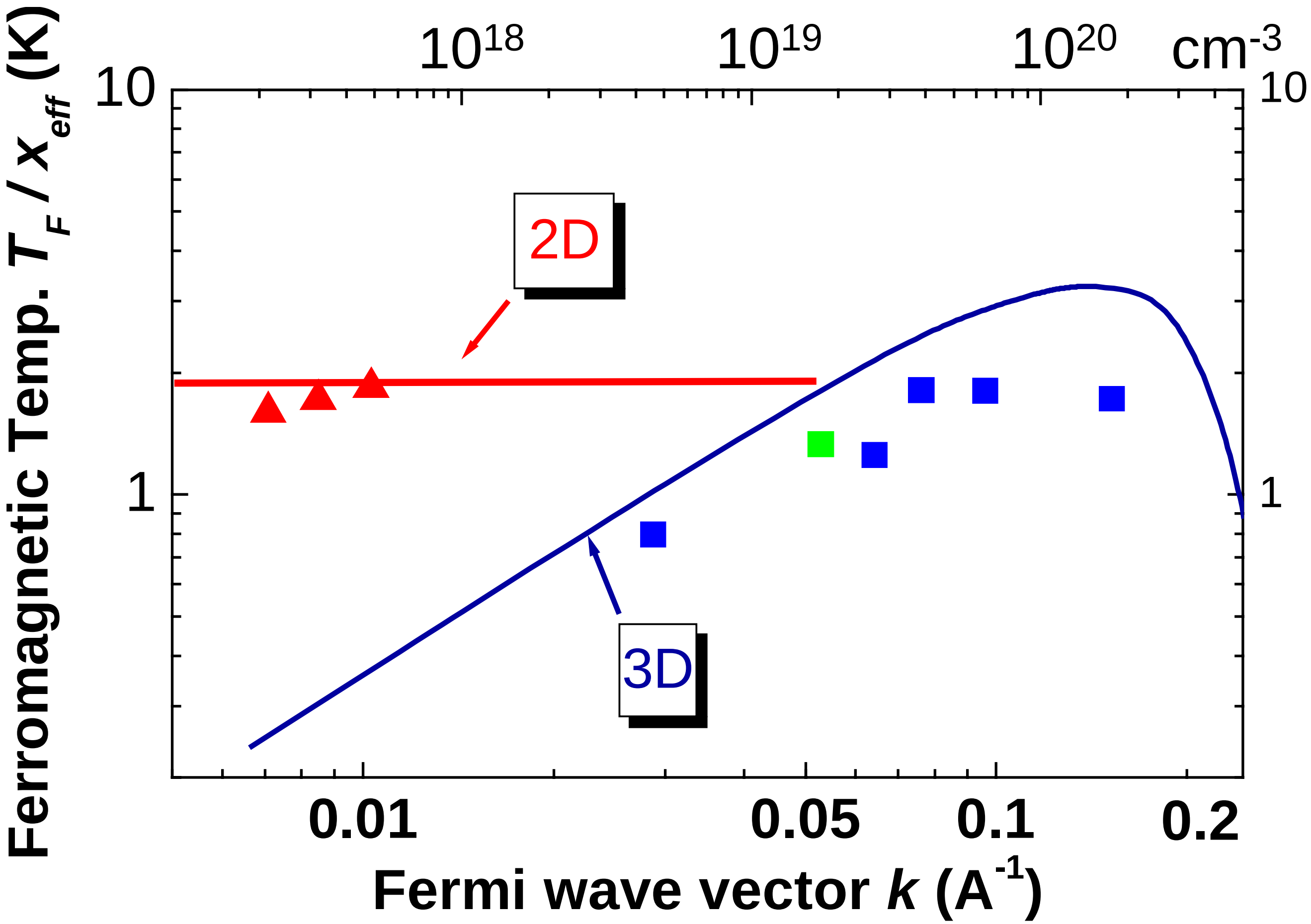
Tuning of magnetic ordering by electrostatic gates (ferro-FET)

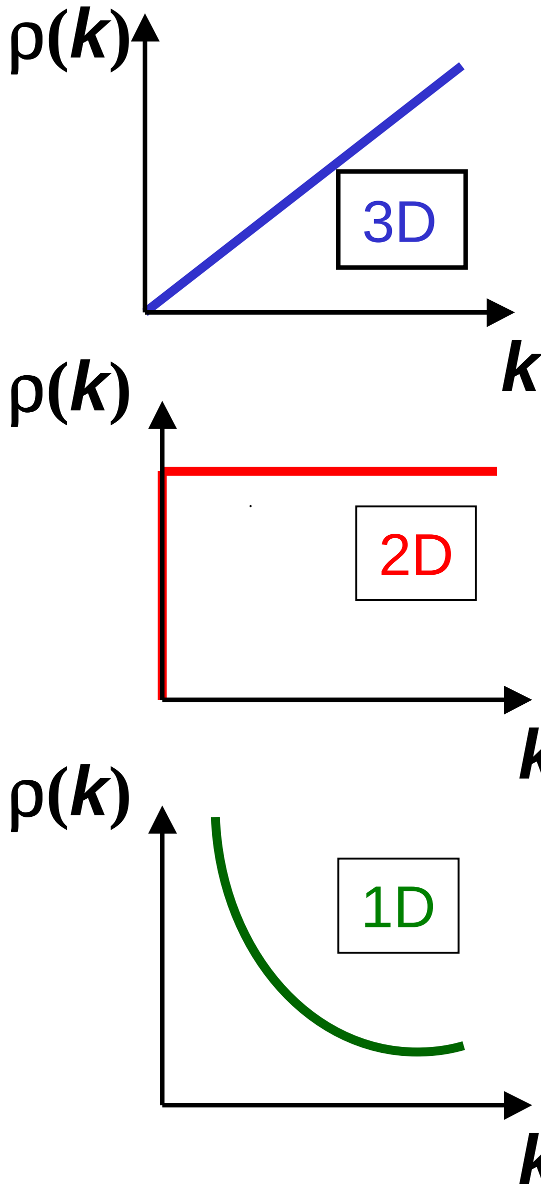




H. Ohno, .., T.D., ...Nature '00

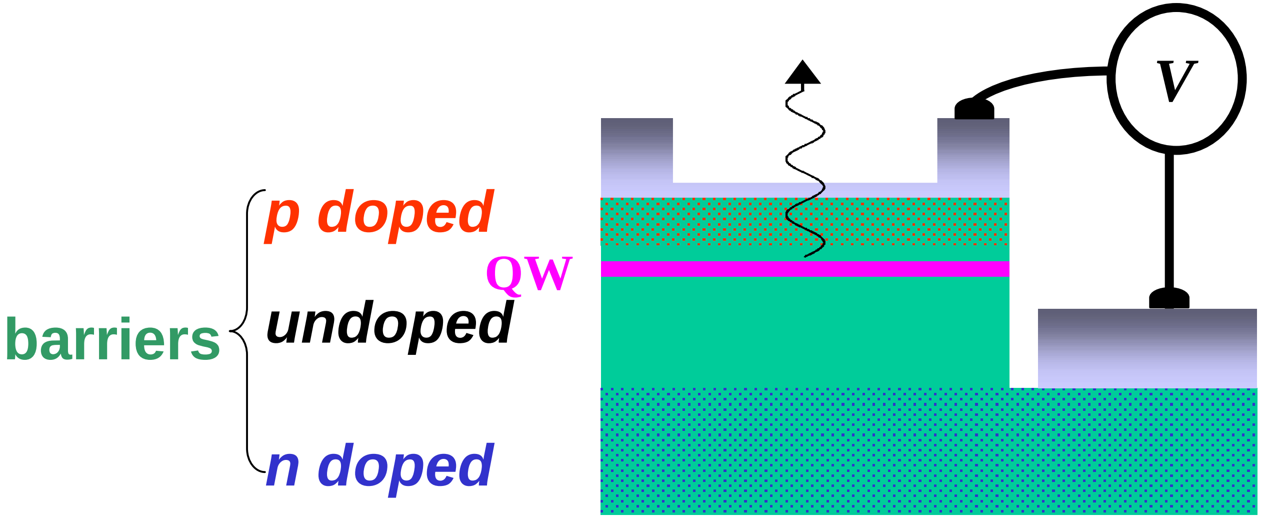
Ferromagnetic temperature in 2D p-$Cd_{1-x}Mn_xTe$ QW and 3D $Zn_{1-x}Mn_xTe$:N



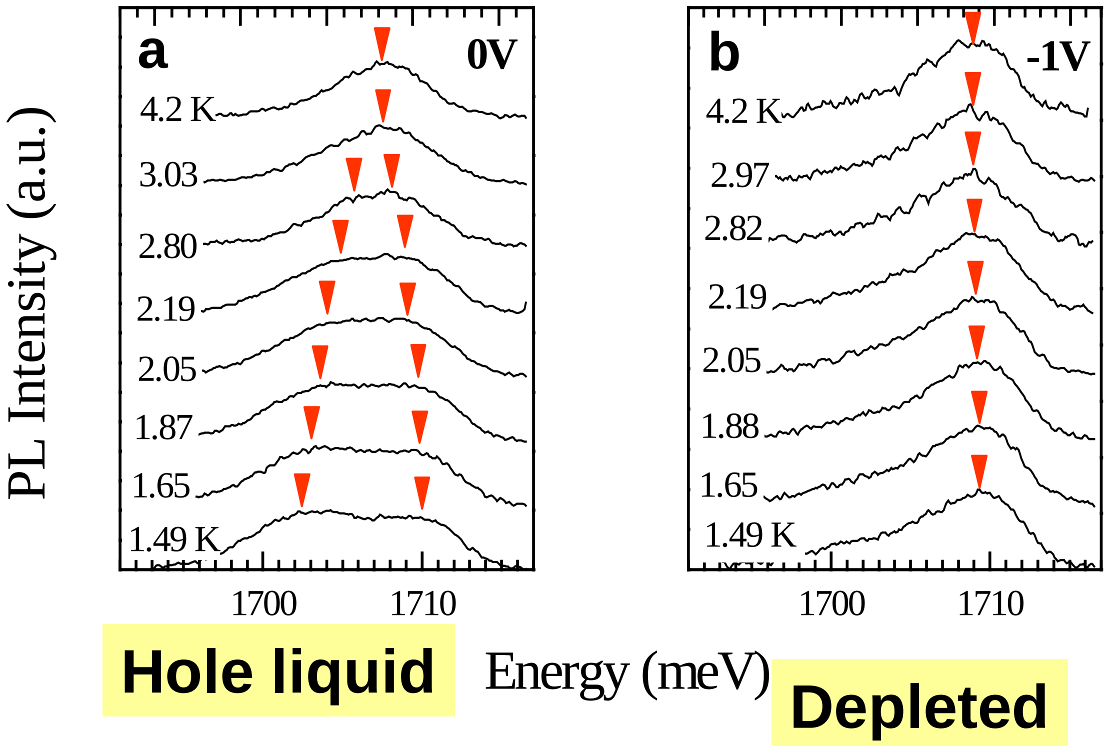


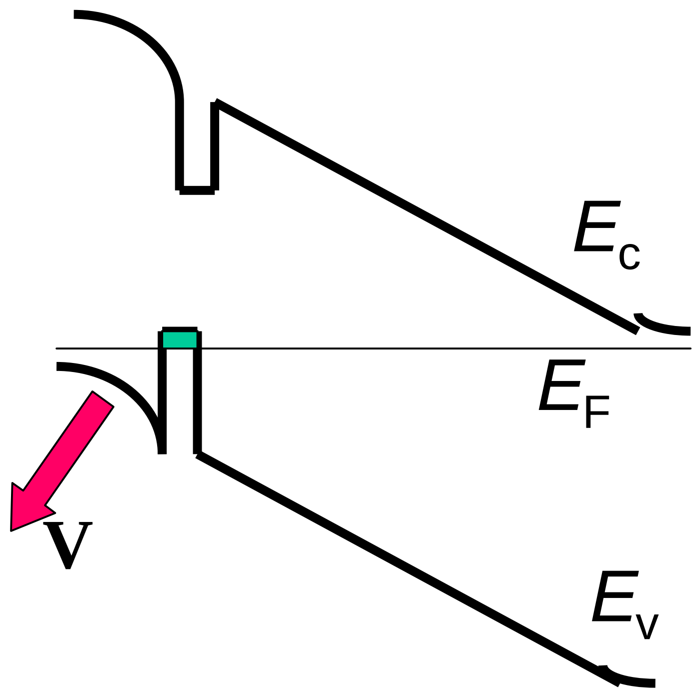
H. Boukari, ..., T.D., PRL'02
D. Ferrand, ... T.D., ... PRB'01

Control by electrostatic gate in a *pin* diode – ferro-LED



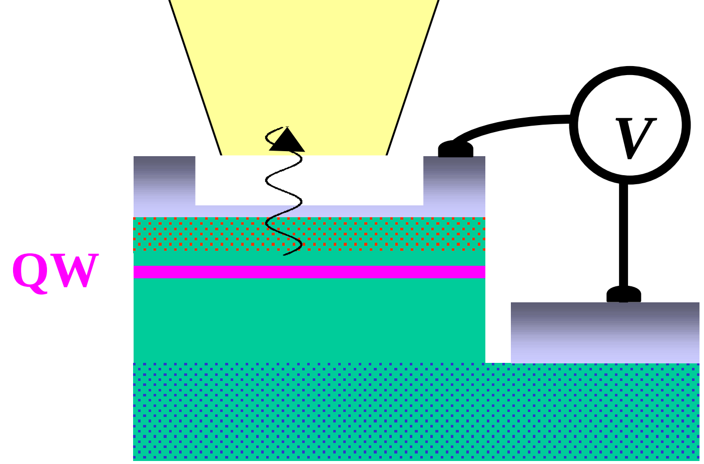
Photoluminescence

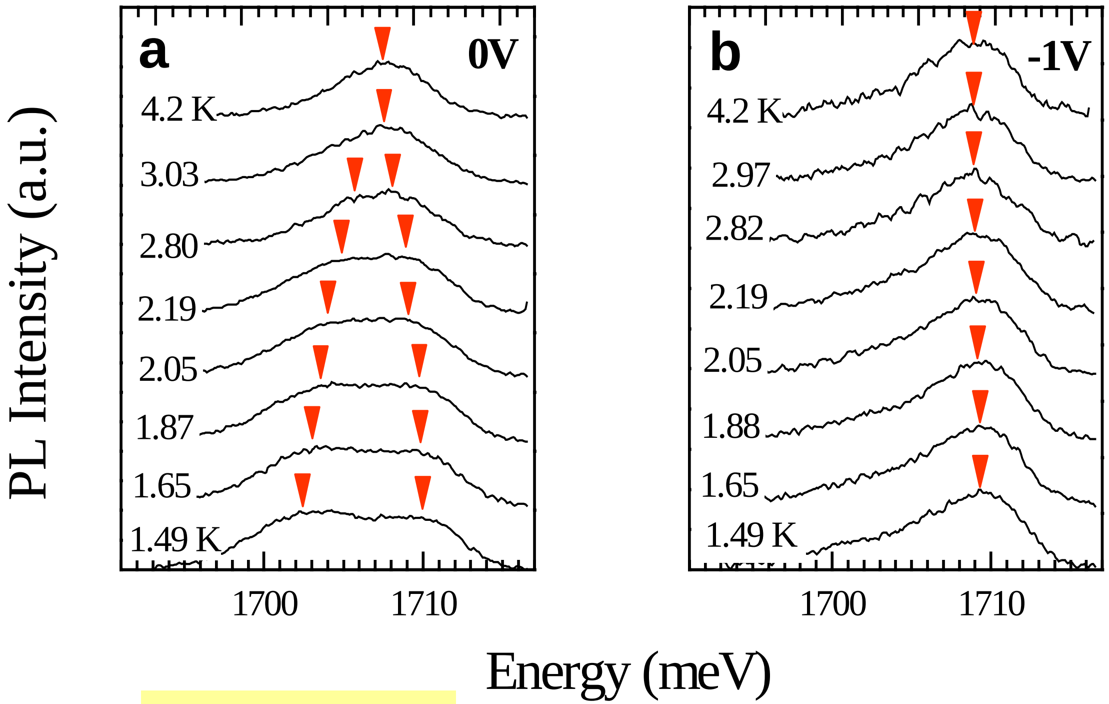




PRL'02

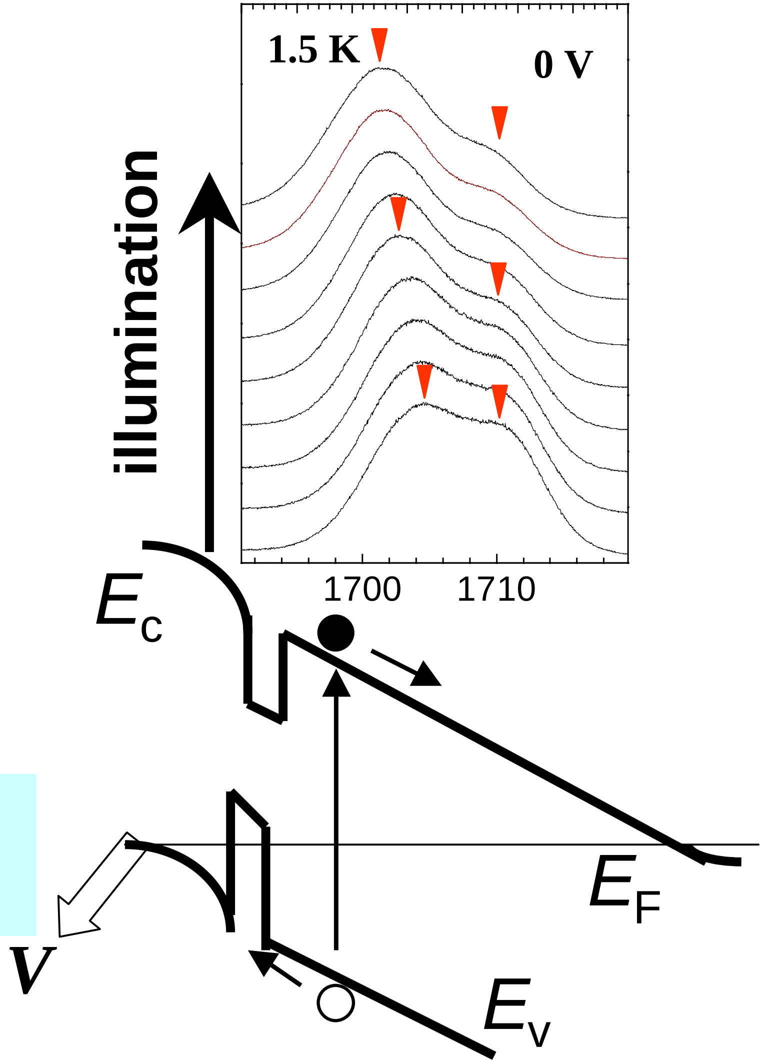
Combined: electrostatic gate + illumination in *pin* diode (ferro-LED)





Hole liquid

Depleted

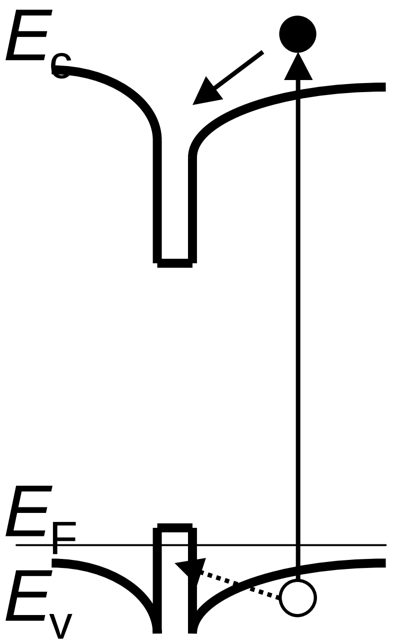


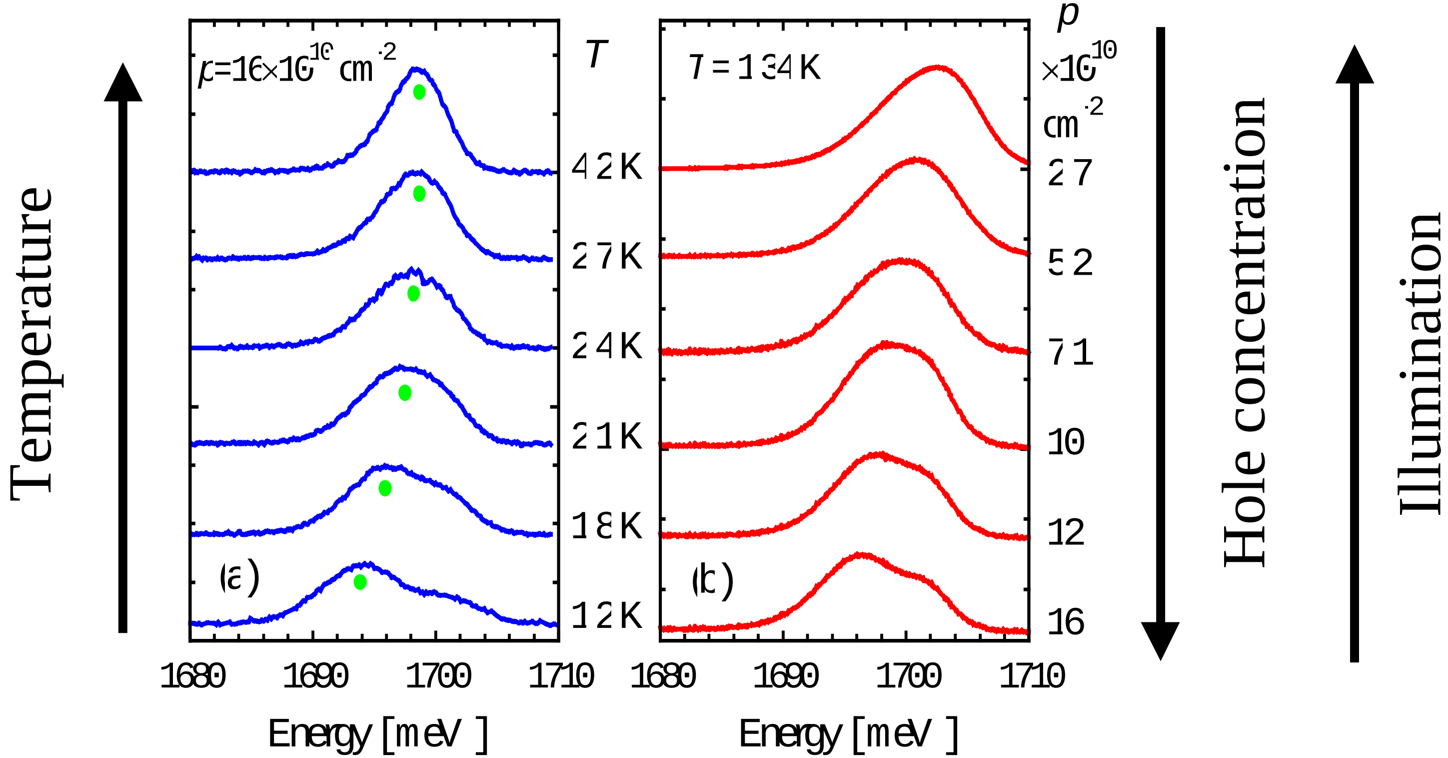
***Ferro-* diode:**
electric field and light tuned ferromagnetism

PRL '02

Optical tuning of magnetization - *pip* diode

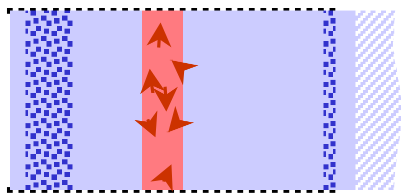
paramagnetic





CdMnTe QW

8 nm



p = const

ferromagnetic

T = const

PRL'02

***pip* diode: light destroys ferromagnetism**

Zinc-blende ferromagnetic semiconductors - highlights

- **Spin injection**

  - (Ga, Mn)As/(Ga,In)As (St. Barbara, Sendai)

- **Dimensional effects**

  (Cd,Mn)Te, (Zn,Mn)Te (Grenoble, Warsaw)

- **Isothermal transition para <--> ferro**

  - light (In,Mn)As (Tokyo); (Cd,Mn)Te (Grenoble, Warsaw)

  - electric field (In,Mn)As (Sendai); (Cd,Mn)Te (Grenoble, Warsaw)

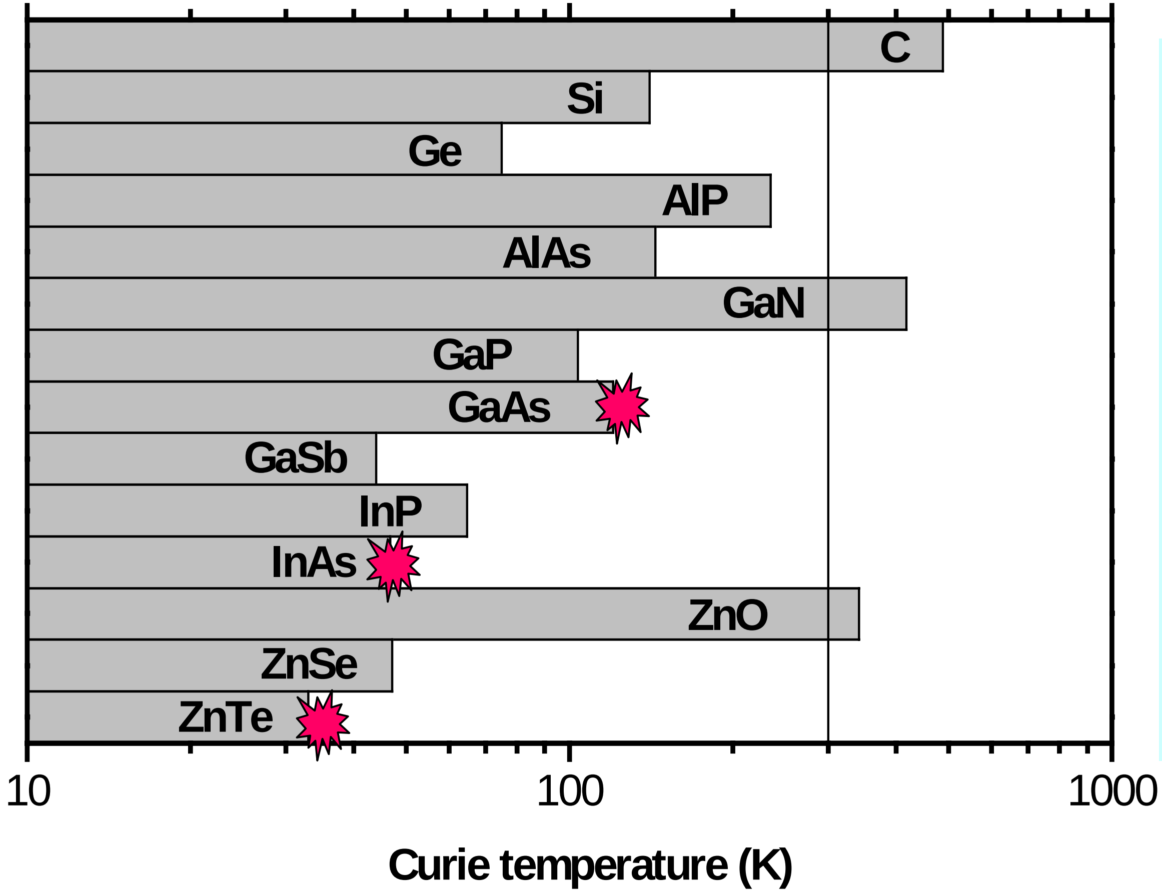
- **GMR** (Ga, Mn)As/(Al,Ga)As/ (Ga, Mn)As (Sendai)

- **TMR** (Ga, Mn)As/AlAs/ (Ga, Mn)As (Sendai, Tokyo)

- **MCD** (Ga, Mn)As (Warsaw, Tsukuba, St. Barbara)

- **Strain engineering** (Ga, Mn)As (Sedai, Tokyo, Warsaw)

Chemical trends – hole driven ferromagnetism
$x_{Mn} = 0.05$, $p = 3.5 \times 10^{20}\ cm^{-3}$



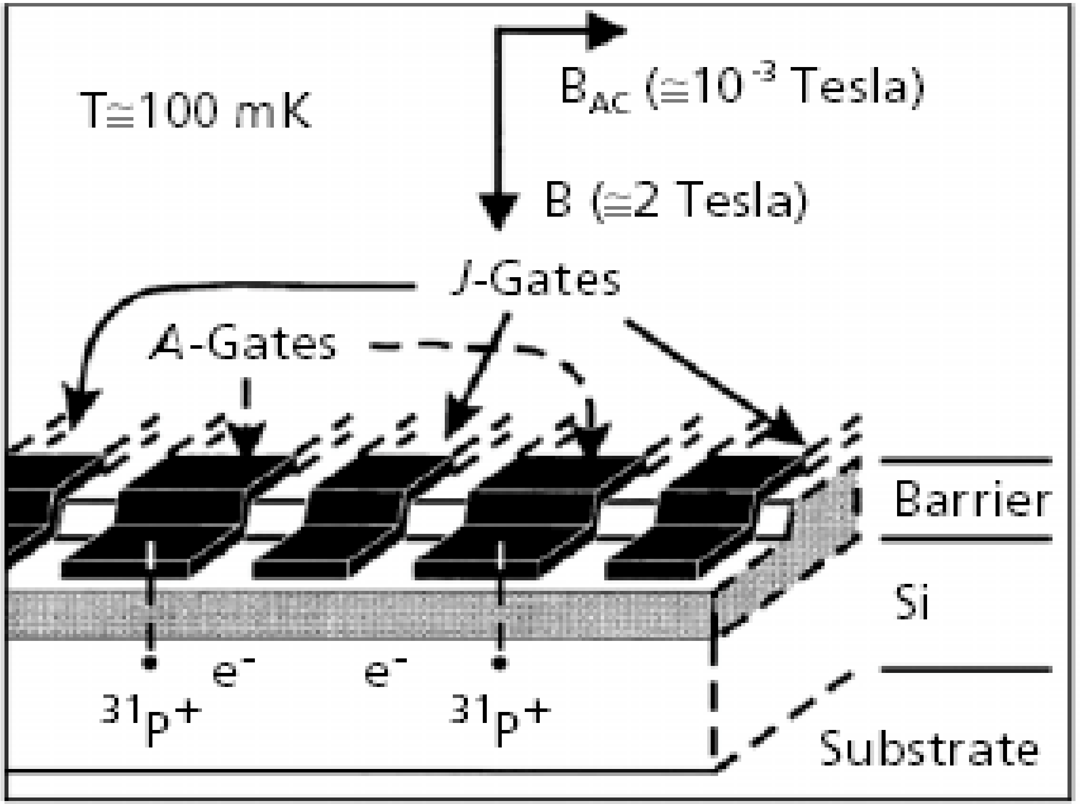
Materials of light elements*:*

- **large p-d hybridization**
- **small spin-orbit interaction**

T.D. et al., Science ‘00

Quantum information hardware

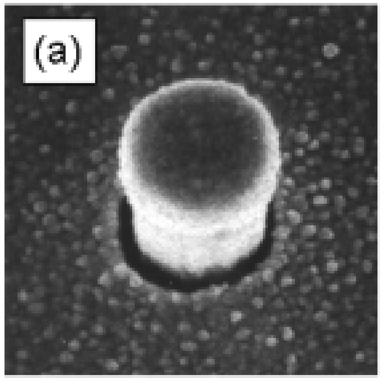
A model of quantum computer, ^{28}Si:^{31}P

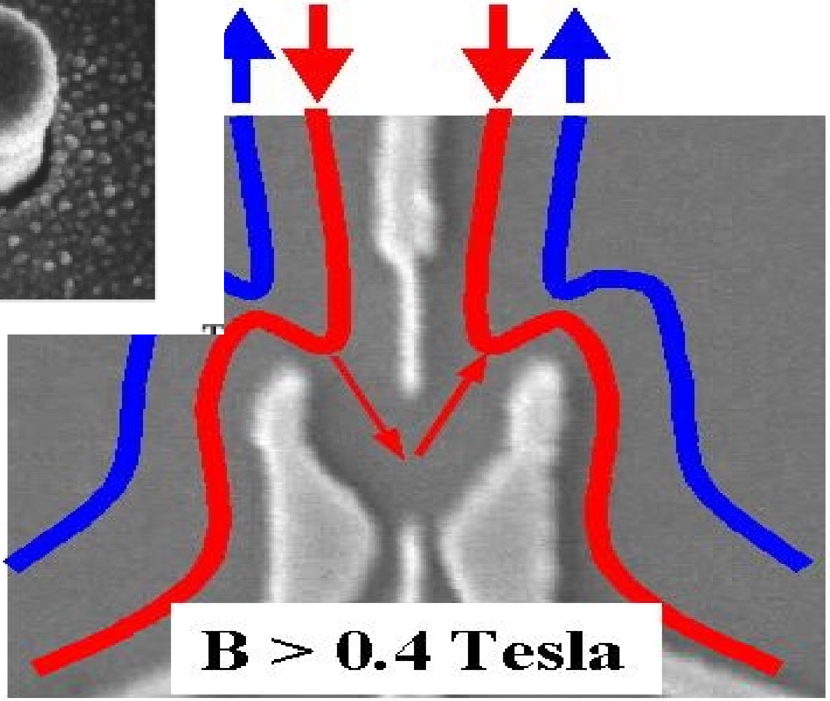


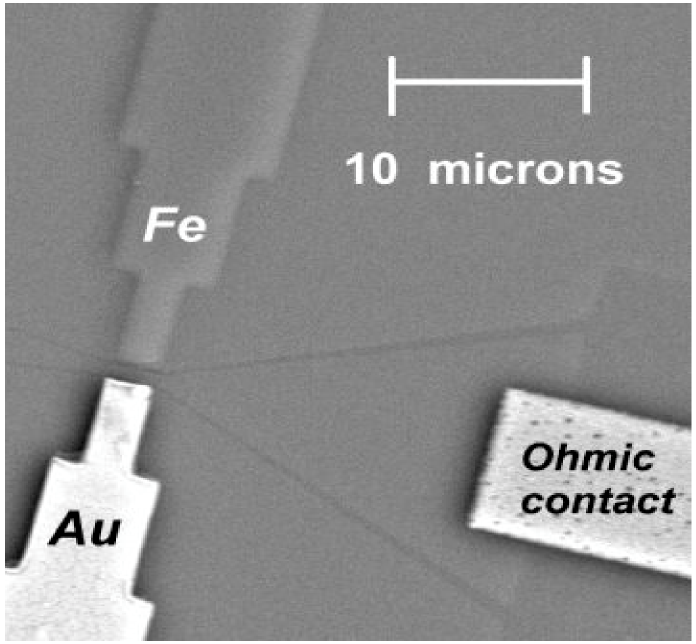
Kane, Nature'98
cf. Loss, DiVincenzo PRA'98

- **qubit**: nuclear spin $I = ½$ of Phosphorous donor impurity
- **single qubit operations**: *A* gates affect hyperfine interaction
- **two qubit operations**: *J* gates affect e-e exchange interaction
- **silicon**: ^{28}Si – no nuclear moments, weak spin-orbit interaction

Towards quantum gates of quantum dots







expl. Delft, Munich, Ottawa, Rehovot, Tokyo, Warsaw, Wuerzburg, ….
theory: Basel, Modena, Ottawa, Paris, Sapporo, Wroclaw, …

Spin molecules: cf. B. Barbara talk
Quantum optics: cf. A. Zeilinger talk

Summary: trends in semiconductor spintronics

- **Physics of spin currents**
  -- injection, transport, coherence, new devices
- **Spin manipulation**
  -- isothermal and fast magnetization reversal
  -- single spin manipulation, magnetometry, entanglement
- **Search for high temperature ferromagnetic semiconductors**
  -- carrier-controlled ferromagnetism
  -- intrinsic ferromagnetism

warning: precipitates and inclusions often present

Thanks to colleagues in Warsaw and to:
I. Solomon, Y. Merle d'Aubigne, H. Ohno, A.H. MacDonald, …