Development of simulation tools for devices based on magnetic semiconductors

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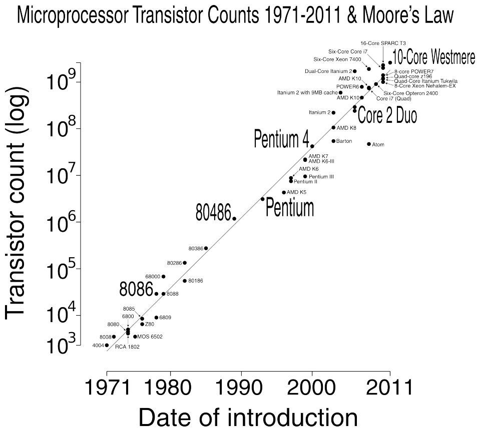
Información

Contents

Contents

Integration limit! Moore's Law

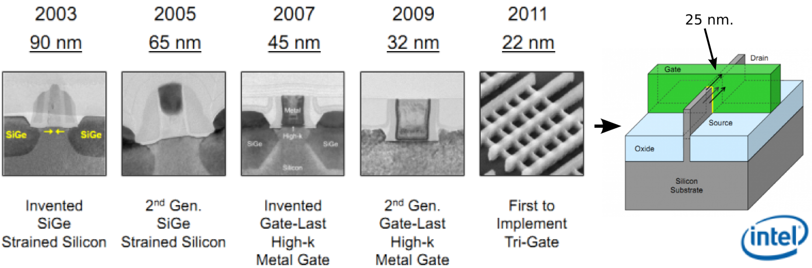


2011:
Westmere-EX (32 nm).

2012:
Ivy Bridge-HE-4 (22 nm).

The complexity for minimum component costs increases at a rate of roughly a factor of two per year.

Integration limit! ITRS



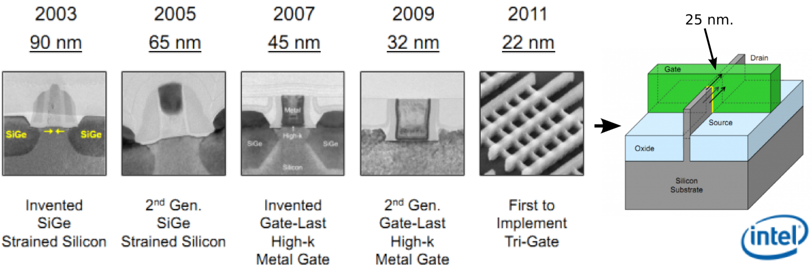
22 nm technological node

$$25 \text{ nm gate length} \times \frac{1 \text{ silicon cell}}{0{,}5 \text{ nm}} \times \frac{8 \text{ silicon atoms}}{1 \text{ silicon cell}} \sim 350 \text{ atoms!!}$$

Typical doping: 1 impurity atom per million of silicon.

Then, maybe, no doping in the device!!!

Integration limit! ITRS



2003	2005	2007	2009	2011
90 nm	65 nm	45 nm	32 nm	22 nm
Invented SiGe Strained Silicon	2nd Gen. SiGe Strained Silicon	Invented Gate-Last High-k Metal Gate	2nd Gen. Gate-Last High-k Metal Gate	First to Implement Tri-Gate

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Integration limit! ITRS

Reduction problems

- ▷ Diferent device properties under same fabrication conditions.
- ▷ Loss of control on the transistor current.
- ▷ Leackage currents (Tunnel current).
- ▷ More energy density (Heating!).
- ▷ Quantum phenomena.

“Traditional” solutions

- ▷ Increasing doping (Degenerate semiconductors).
- ▷ Exotic geometries (Double gate, Trigate, nanowires...).
- ▷ New materials to avoid leaking (High-K oxides).
- ▷ Reduction of the ON/OFF voltage/current levels.
- ▷ New physical models (Density-gradient, Green, Schrödinger).

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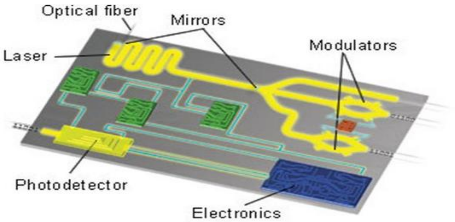
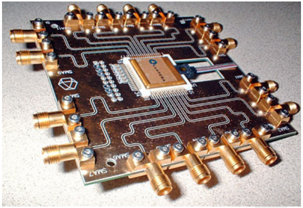
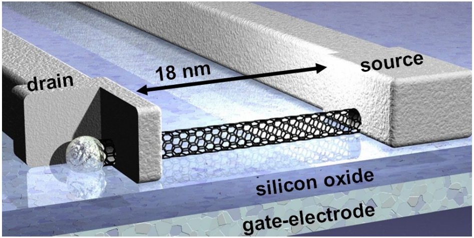
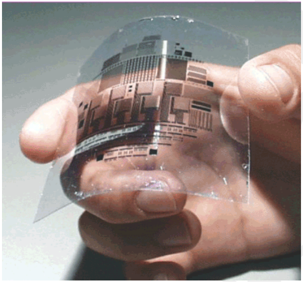
Alternatives to Electronics

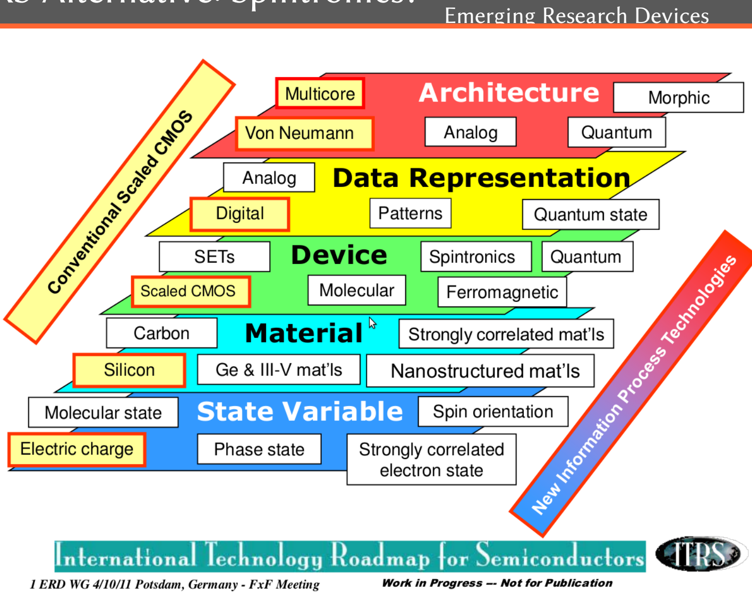








ITRS Alternative: Spintronics?



Emerging Research Devices

Conventional Scaled CMOS

Architecture
Multicore
Von Neumann
Analog
Quantum
Morphic

Data Representation
Analog
Digital
Patterns
Quantum state

Device
SETs
Scaled CMOS
Molecular
Spintronics
Quantum
Ferromagnetic

Material
Carbon
Silicon
Ge & III-V mat'ls
Strongly correlated mat'ls
Nanostructured mat'ls

State Variable
Molecular state
Electric charge
Phase state
Spin orientation
Strongly correlated electron state

New Information Process Technologies

International Technology Roadmap for Semiconductors

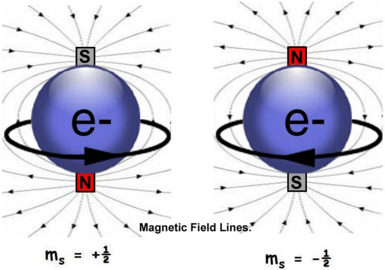
ITRS

1 ERD WG 4/10/11 Potsdam, Germany - FxF Meeting

Work in Progress -- Not for Publication

What is electron spin?

Spin is an intrinsic form of angular momentum
carried by elementary particles.

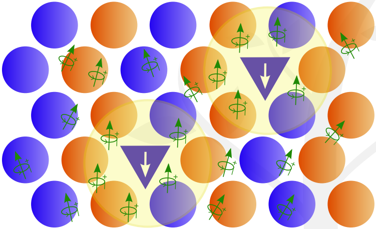


Diluted Magnetic Semiconductors (DMS)

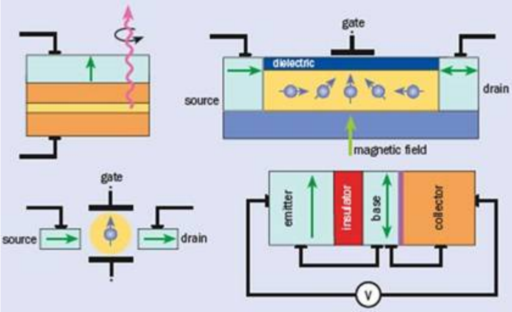
- Magnetic semiconductors: Integration with electronics.
- Spin polarization control. Intrinsically and/or externally.
- Good at T ~ 0 K. Research on alloys for room temperatures.
- (III-V) and (II-VI) compounds doped with Mn, Co, Cr...
- $(Ga_{1-x},Mn_x)As$: Mn provides spin and polarize hole spin.
- $(Zn_{1-x},Co_x)O$: Co provides spin and polarize electron spin.
- High doping concentration: up to 15 % (vs. $\sim$ 0,001 %).

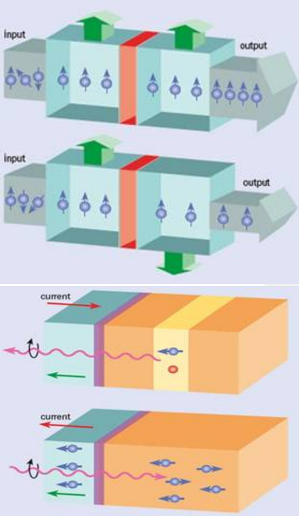
Transition temperatures

- GaAs: 170 K
- ZnO: 350 K
- GaN: 450 K
- Si: 130 K
- C: 490 K



Spintronic devices





Contents

Hypothesis and Objectives

Hypothesis

- ▷ Is it possible to simulate the electrical response of spintronic devices using the techniques of electronics?
- ▷ Is the drift-diffusion model still valid for the transport of the spin?

Objectives

- ▷ Create a set of tools to simulate basic spintronic devices.
- ▷ Simulate the diode and tunnel barrier and check with experiment if possible.

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Simulation strategy

Simulation problems

- ▷ Heavily doped materials. Is drift-diffusion model not valid?
- ▷ Quantum-mechanical tunnel transport.
- ▷ Interfaces between diferent materials.
- ▷ Spin polarization. How it affects to the models?
- ▷ Exotic materials as semiconductors: (Ga,Mn)As, (Zn,Co)O

Solutions

- ▷ Drift-diffusion can be still valid. Correction factors!
- ▷ Non-local tunnel recombination.
- ▷ Graded junctions and thermoinic emision model.
- ▷ Zeeman effect: Energy band splitting.
- ▷ Property parametricing. Literature survey.

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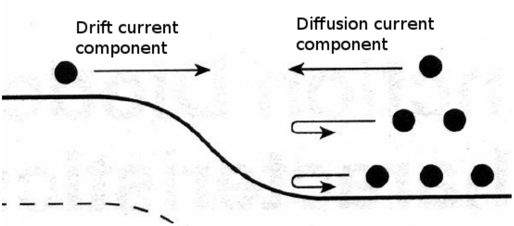
Drift-diffusion model

Low doped systems

$$\text{Current} = \text{Drift Current} + \text{Difussion Current} = \alpha n\vec{E} + \beta\frac{dn}{dx}$$



- ▷ Low impurity levels.
- ▷ Low electric fields.
- ▷ Low levels of current.

Heavily doped systems

$$\text{Current} = \alpha n(\vec{E} + \vec{E}_{corr}) + \gamma_{corr}\beta\frac{dn}{dx} = \alpha n\vec{E} + \gamma_{deg}\beta\frac{dn}{dx}$$

Drift-diffusion model

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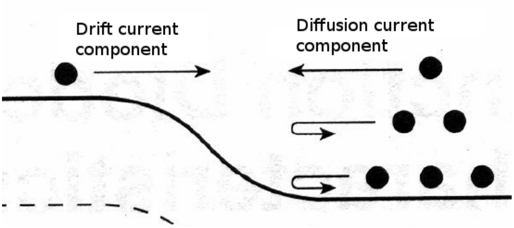

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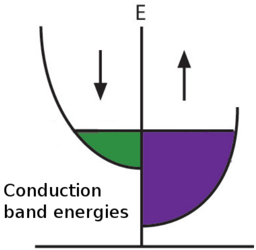
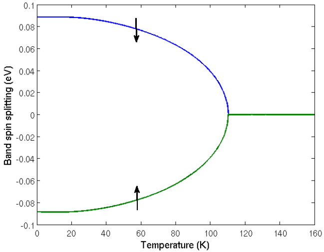
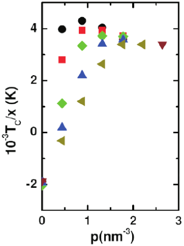
Zeeman effect: Energy band splitting





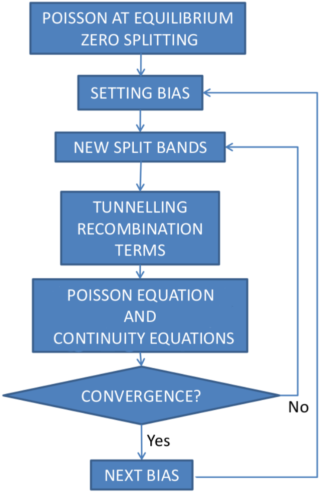


- ▷ Spin split bands are created by mangnetization in the material.
- ▷ Depends on the impurity magnetic moments and temperature.
- ▷ Critical temperature depends on electron/hole concentration.

Simulator structure

- 1 dimensional simulator.
- Finite diferences method.
- Band splitting updated in each iteration.
- Tunnel recombination for each band.
- Solve poisson, electron and hole equations:

$$\nabla(\epsilon\nabla V) = q_e\left(p - n + N_D^+ - N_A^-\right)$$
$$\nabla \vec{J}_{n\uparrow} = q_e R_{tun}^{e\uparrow - h\downarrow}$$
$$\nabla \vec{J}_{n\downarrow} = q_e R_{tun}^{e\downarrow - h\uparrow}$$
$$\nabla \vec{J}_{p\uparrow} = -q_e R_{tun}^{e\downarrow - h\uparrow}$$
$$\nabla \vec{J}_{p\downarrow} = -q_e R_{tun}^{e\uparrow - h\downarrow}$$



POISSON AT EQUILIBRIUM ZERO SPLITTING

SETTING BIAS

NEW SPLIT BANDS

TUNNELLING RECOMBINATION TERMS

POISSON EQUATION AND CONTINUITY EQUATIONS

CONVERGENCE?

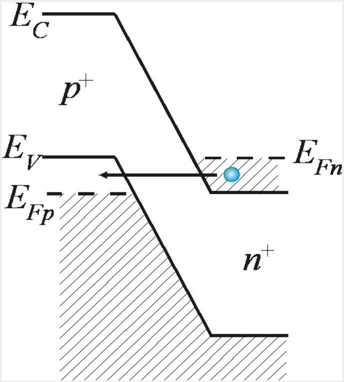
No

Yes

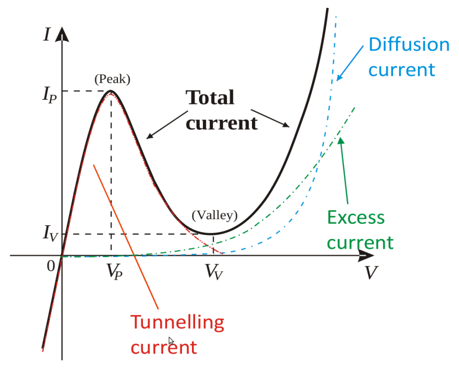
NEXT BIAS

Tunnel diode

Energy bands

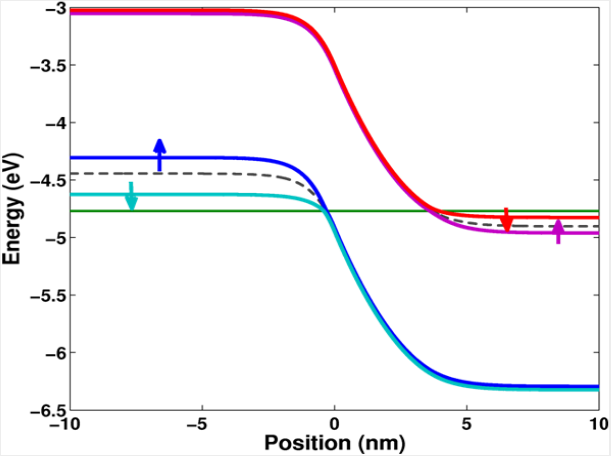


I-V characteristic



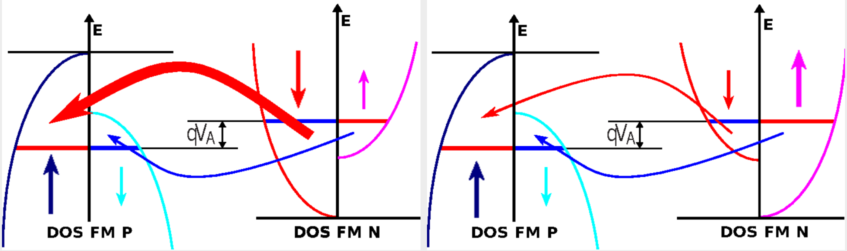
Tunnel diode

Spin split bands



Tunnel diode

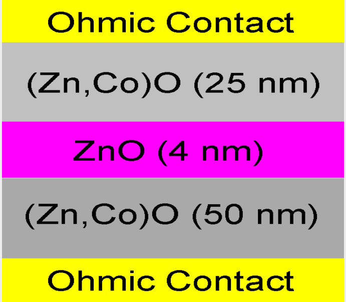
Tunnel transport



- ▷ Tunneling recombination reevaluated: $R_{e\uparrow - h\downarrow}$ and $R_{e\downarrow - h\uparrow}$.
- ▷ Tunneling between the majority (minority) bands $I_{ap}(V_A)$.
- ▷ Tunneling between majority and minority bands $I_p(V_A)$.
- ▷ $\mathrm{TMR}(V) = \frac{|I_p(V) - I_{ap}(V)|}{I_p(V) + I_{ap}(V)} \times 100\,\%$

Tunnel barrier

Structure schematic



Ohmic Contact

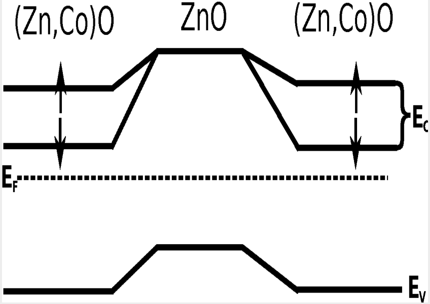
(Zn,Co)O (25 nm)

ZnO (4 nm)

(Zn,Co)O (50 nm)

Ohmic Contact

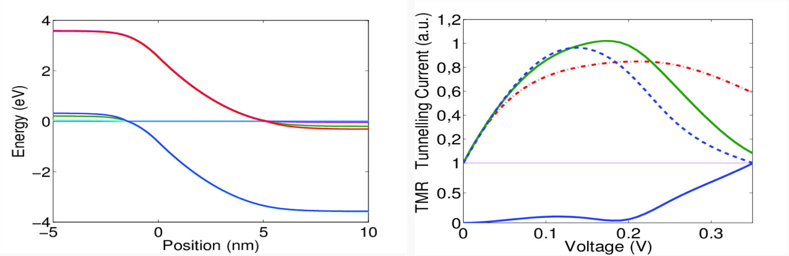
Spin split bands



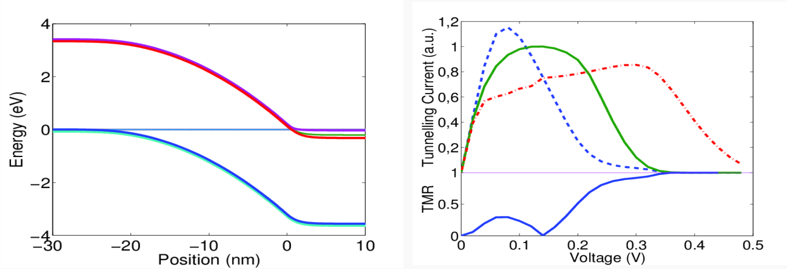
Contents

Tunnel diode results

(Ga,Mn)As



(Zn,Co)O



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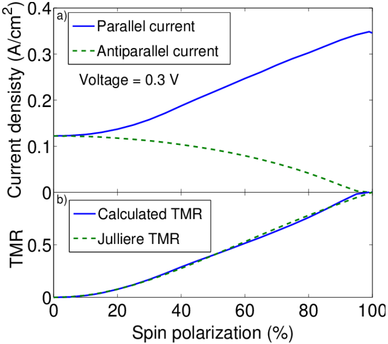
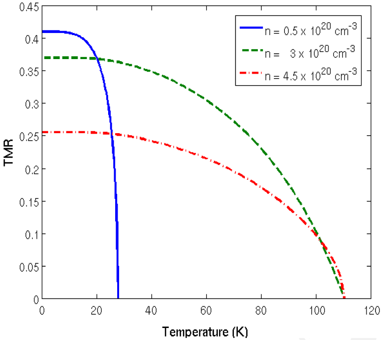


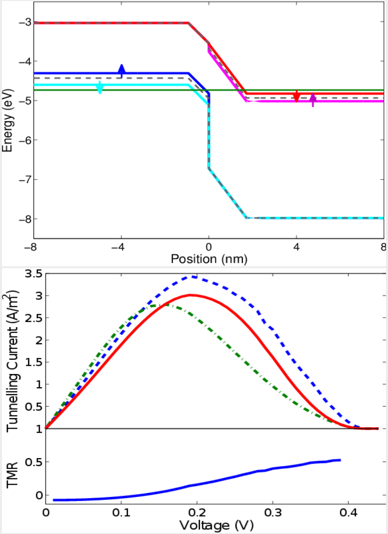


$$\text{Julliere TMR} = \frac{2\times P_{left}\times P_{right}}{1+P_{left}\times P_{right}}$$

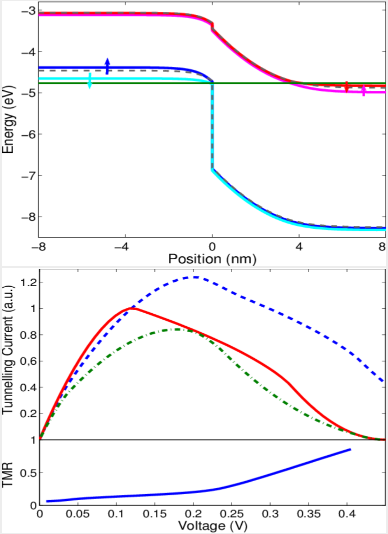
$$\text{TMR} \propto \left(T_C^{\alpha} - T^{\alpha}\right)$$

Tunnel hetero-diode results

Analytical model

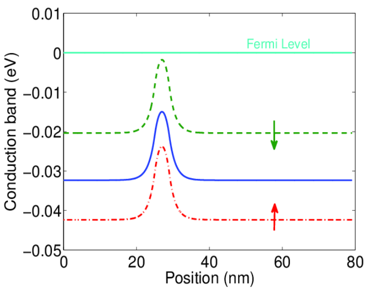


Numerical simulation

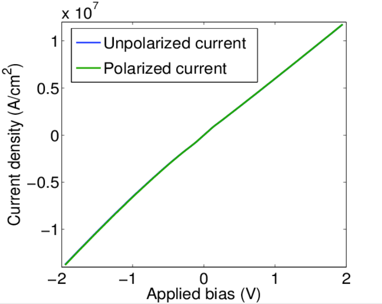


Tunnel barrier results

Simulated split bands



I-V response



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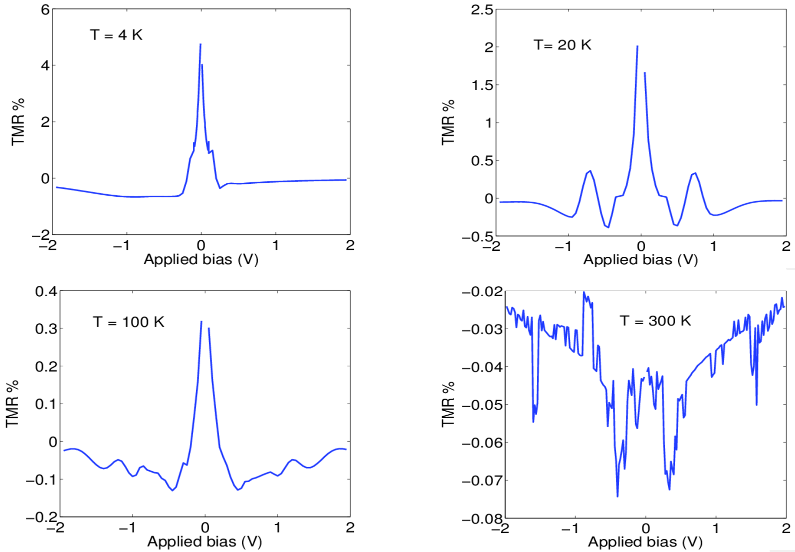

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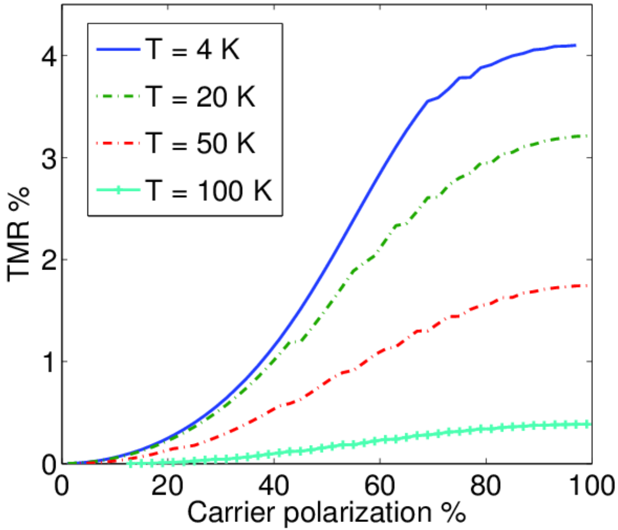

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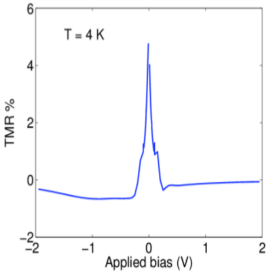
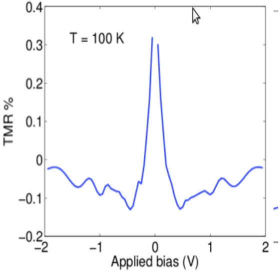
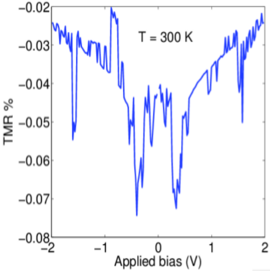
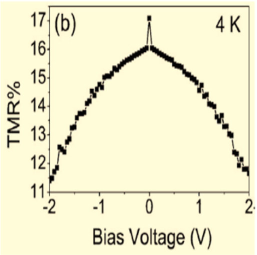
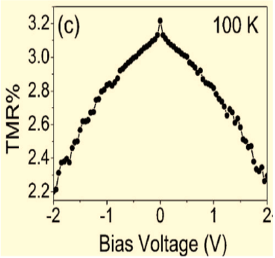
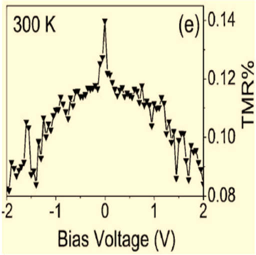












Contents

Conclusions

- ▷ We develop analytical and numerical simulators for spin transport using modified drif-diffusion model.
- ▷ Drift-diffusion model offers a non-costly computational model to check hundreds of systems.
- ▷ We analyze to basic structures in the electronics such as diode and tunnel barrier using the TMR figure of merit.
- ▷ Diode results seem to agree with some experiments and other theoretical works when simulated with drif-diffusion.
- ▷ However tunnel barrier needs more modeling work. We obtain a smaller TMR signal than the experiments.

Future work

- Analyze the behavior of this systems using strongly correlated materials model (Mott materials). Specially the tunnel barrier.
- Analyze the optical response of the materials: Electrical response under polarized ilumination and polarized light emision.

Colaborations

University of Sheffield, UK

Development of suitable models to analyze the ferromagnetic semiconductors.

Host: Prof. Gillian Gehring

University of Swansea, UK

Implementation of the simulator and results checking in Silvaco comercial simulator.

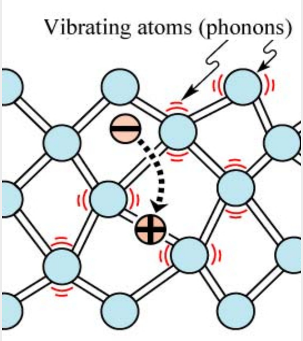
Host: Dr. Karol Kalna

Thank you!

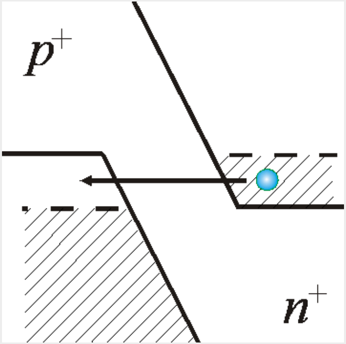
Questions?

Non-local tunnel recombination

Recombination

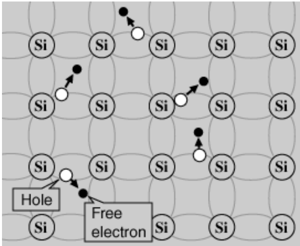


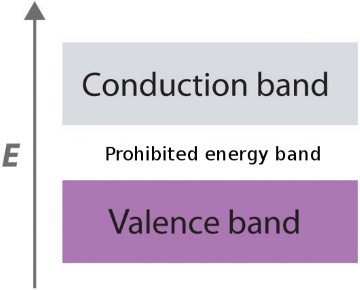
Tunnel Recombination



Tunnel recombination: $R_{tun} \propto |\vec{E}| \times \Gamma_{tun} \times T \times D(\epsilon)$

Energy bands





- ▷ Free electrons created from broken bonds between semicondutor atoms.
- ▷ Free electron (negative) move with conduction band energies.
- ▷ Broken bonds (holes, positive) move valence band energies.