Hybrid Devices and Spin-Dependent Functionality in 6.1 Å Materials

B.T. Jonker

Naval Research Laboratory, Washington, D.C.

- hybrid devices
- spin transport

Spintronic Devices

A. Hanbicki,* Y.D. Park,* S.-F. Cheng, R. Magno & A.S. Bracker

Naval Research Laboratory, Washington, D.C.

A. Petukhov

ONR / ASEE / NRL Visiting Faculty -- South Dakota School of Mines & Technology

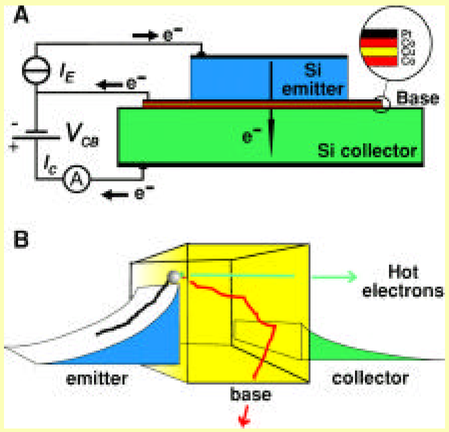
G. Itskos, M. Furis, G. Kioseoglou and A. Petrou

State University of NY, Buffalo

* NRC / NRL Posdoctoral Associates

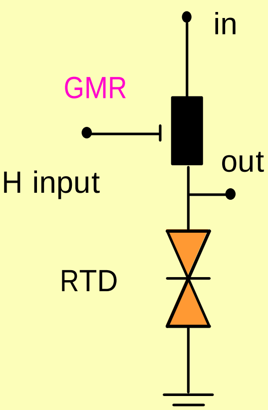
Semiconductor Spintronic Devices

Hybrid Device Structures

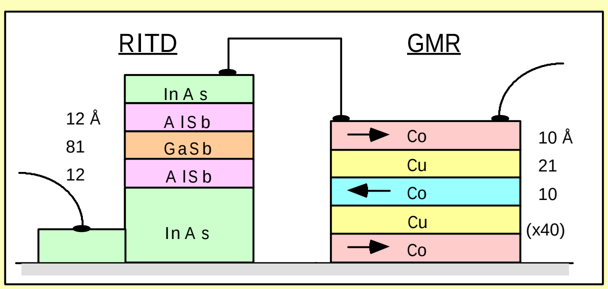


- spin-valve metal-base transistor (Monsma)
- GMR base spin-resistor

Science 281 (1998)



hybrid GMR / RTD



Examples:

- Spin-valve transistor
  D. Monsma *et al.*
  GMR base is variable spin resistor
- Hybrid Hall effect device
  M. Johnson *et al.*
  M. Roukes *et al*.
  fringe fields --> local Hall effect
- Hybrid RTD / GMR structures
  NRL
  6.1 Å materials

Spin transport in semiconductor is NOT necessary for device operation

RTD / GMR Hybrid Devices

Semiconductor RTD

- **Low power operation**
- **High speed operation (ps)**
- **Reduced circuit complexity**

Metallic GMR

- **Spin transport**
- **Average speed operation (ns)**
- ***Nonvolatile & tunable***

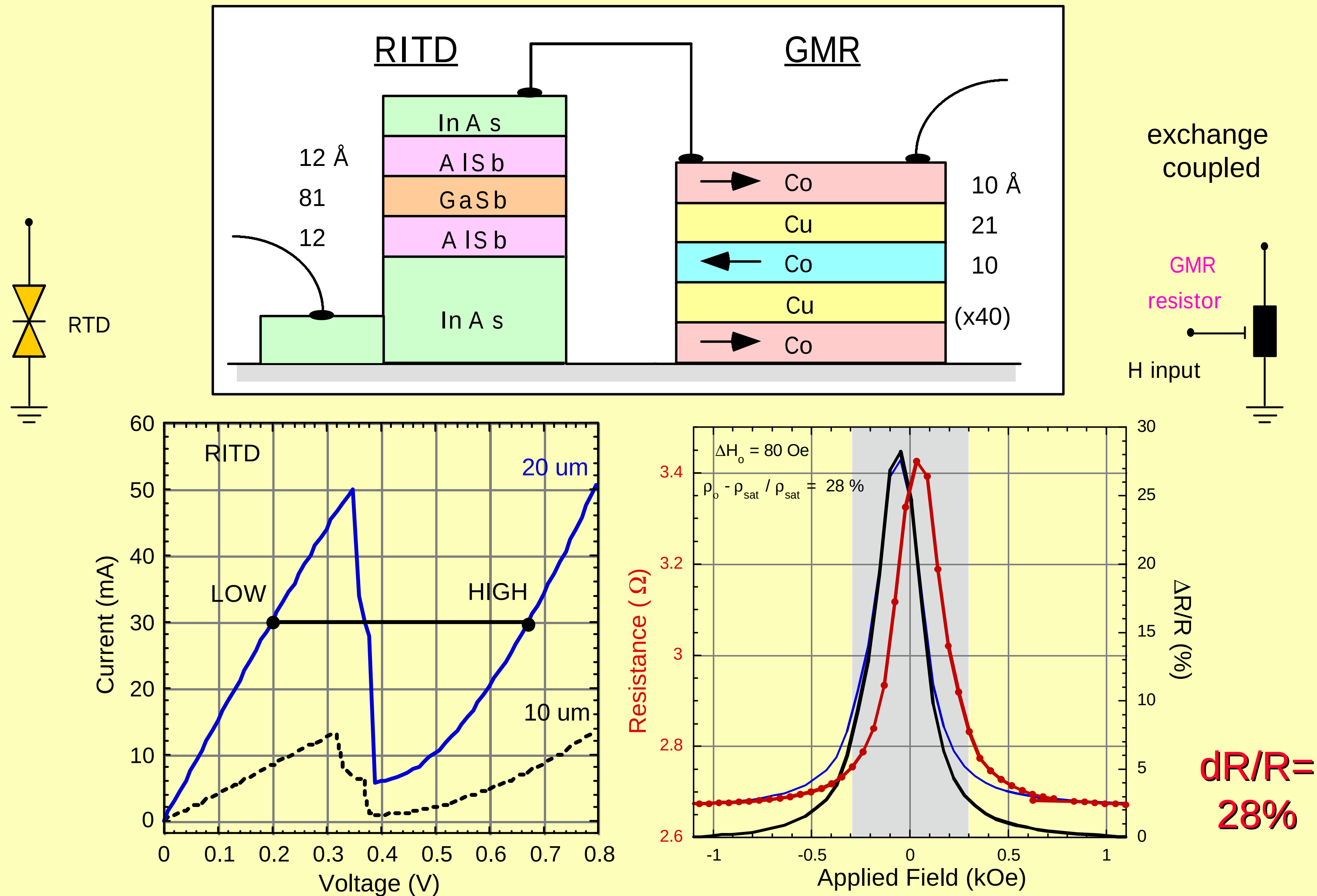
⇒ **Nonvolatile, fully reprogrammable hybrid devices for**

- multiple-valued logic
- multiple-valued memory
- programmable logic cells
- digital signal processing
- field programmable gate arrays

basic *BUILDING BLOCKS* to provide multiple functions

with A. Hanbicki (NRC postdoc), R. Magno, S.-F. Cheng, A. Bracker

RTD / GMR Hybrid Devices



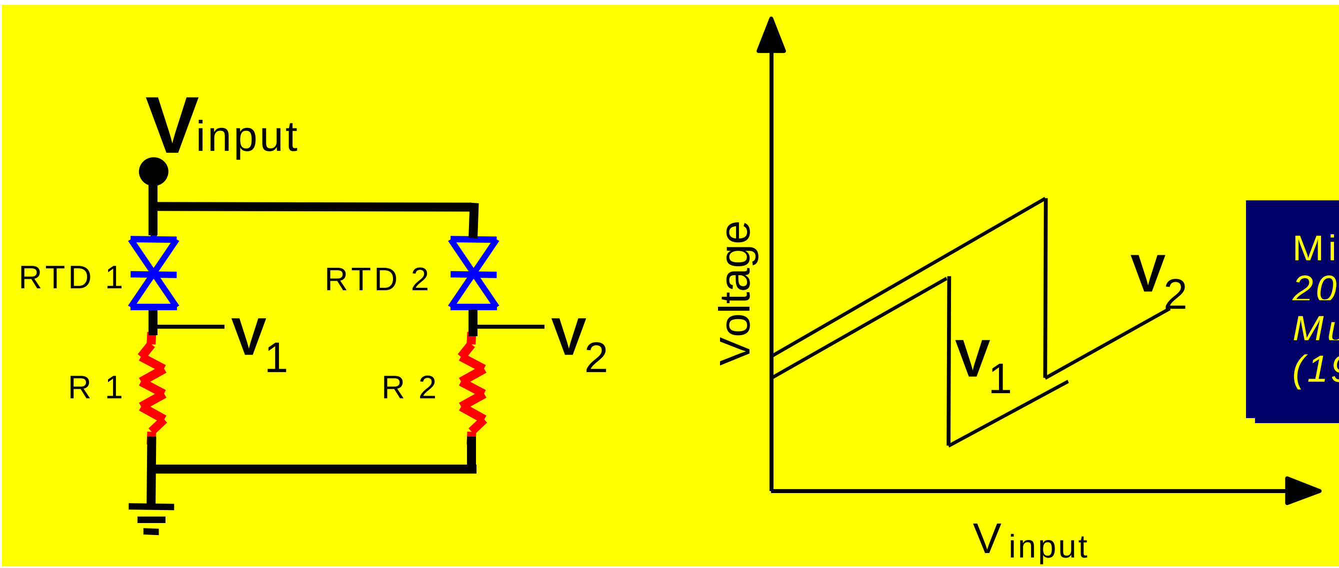
T = 300 K

dR/R= 28%

May 2000

RTD - Resistor: Series Combination

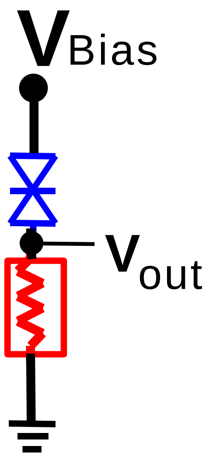
Application: Multiple-Valued Logic (MVL) or Memory

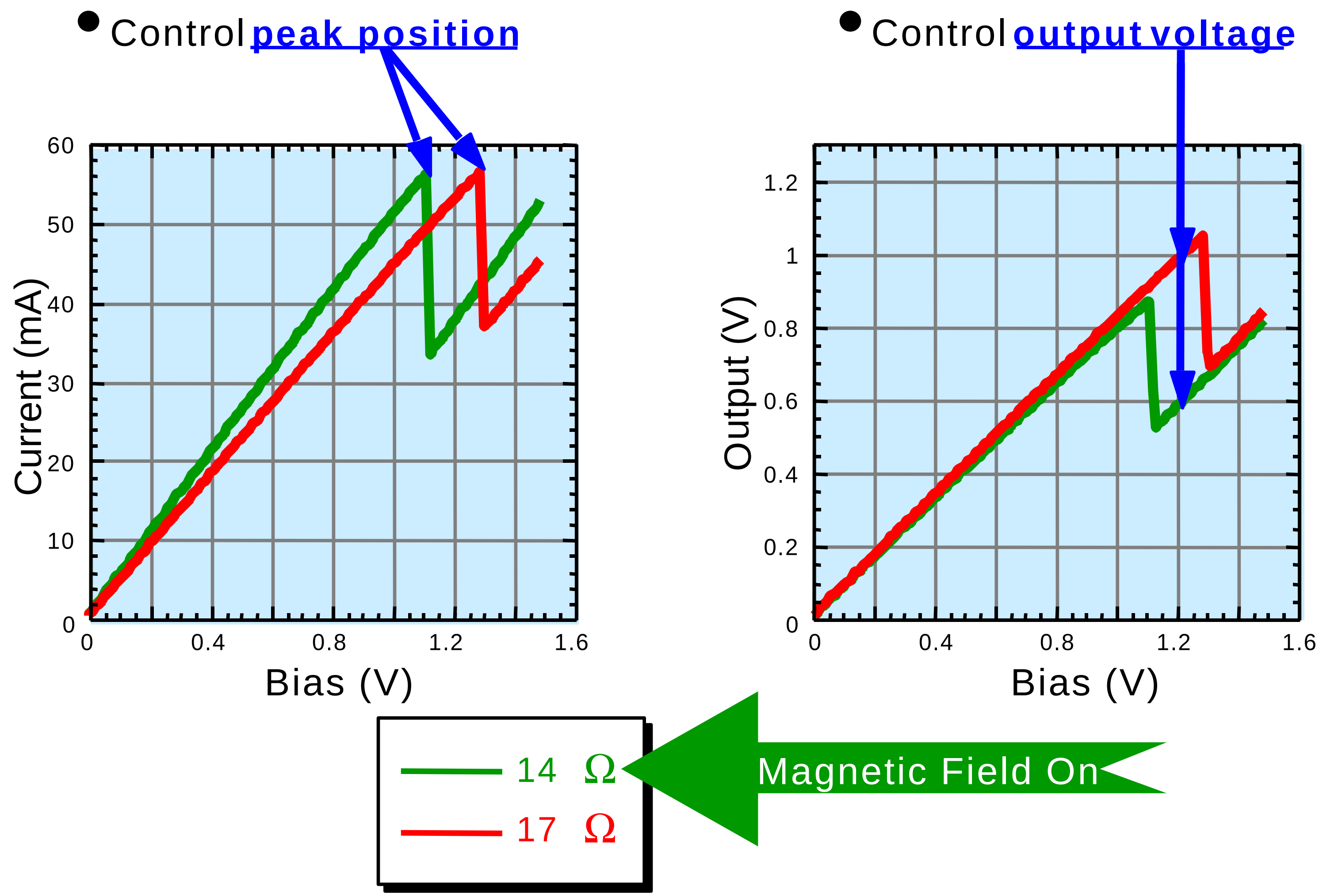


Micheel and Paulu
20th Intl Symp
Multiple-valued Logi
(1990)

RTD - GMR Hybrid: Series Combination

Control the Output: RTD–GMR Series





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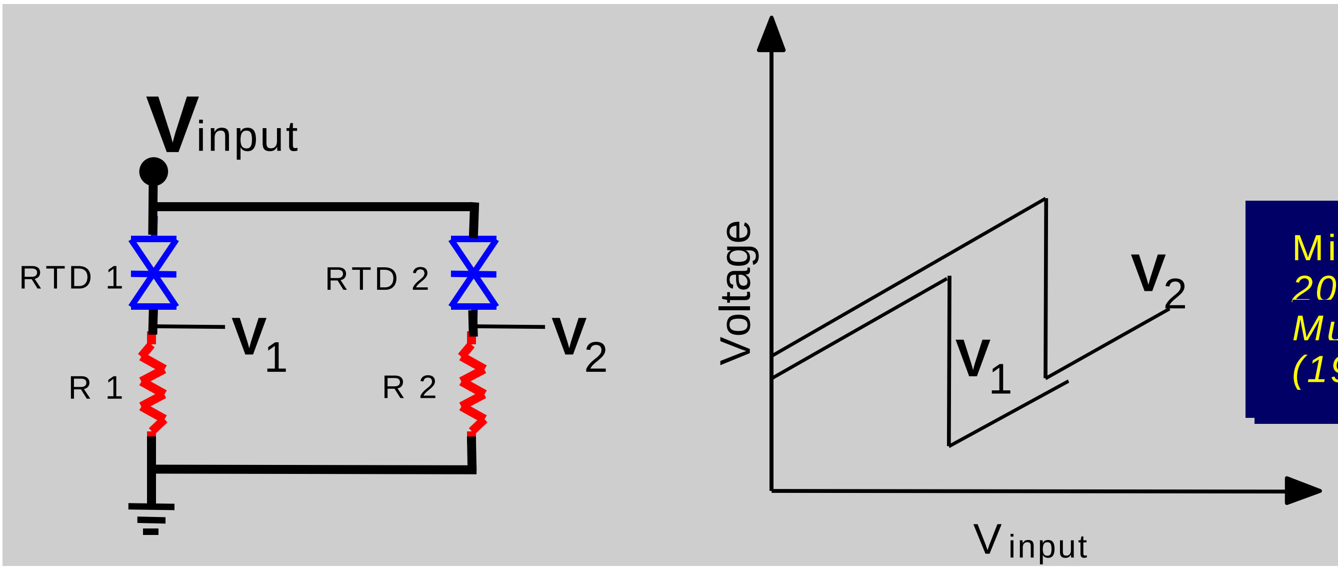
RTD - GMR Hybrid: Series Combination

Application: Multiple-Valued Logic (MVL) or Memory



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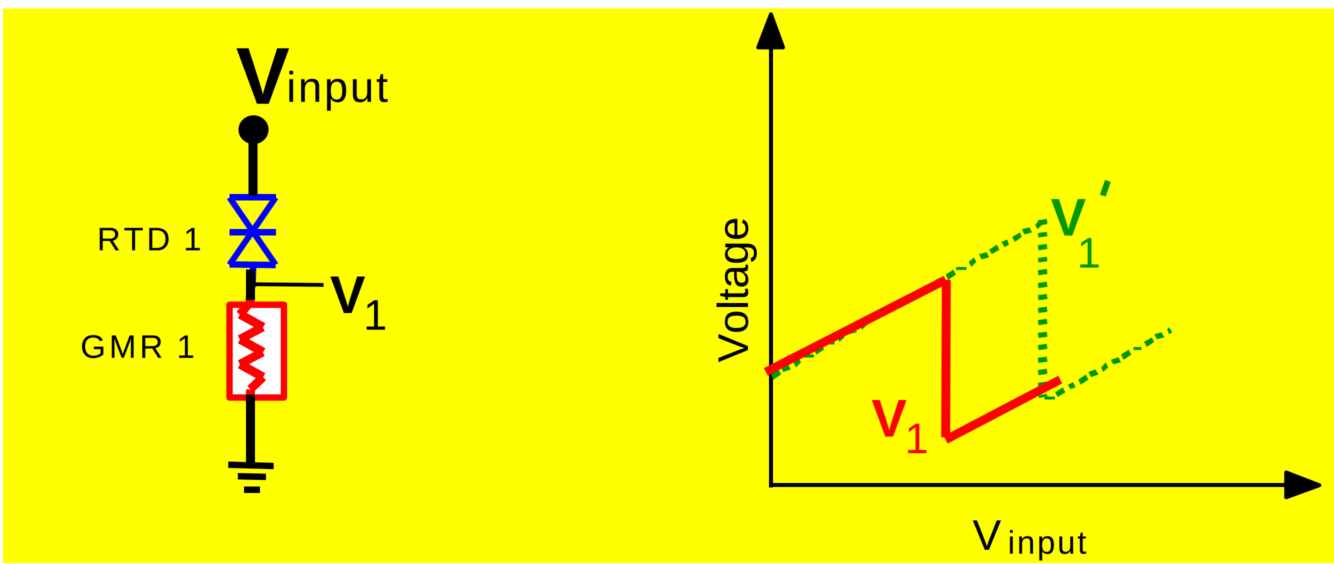
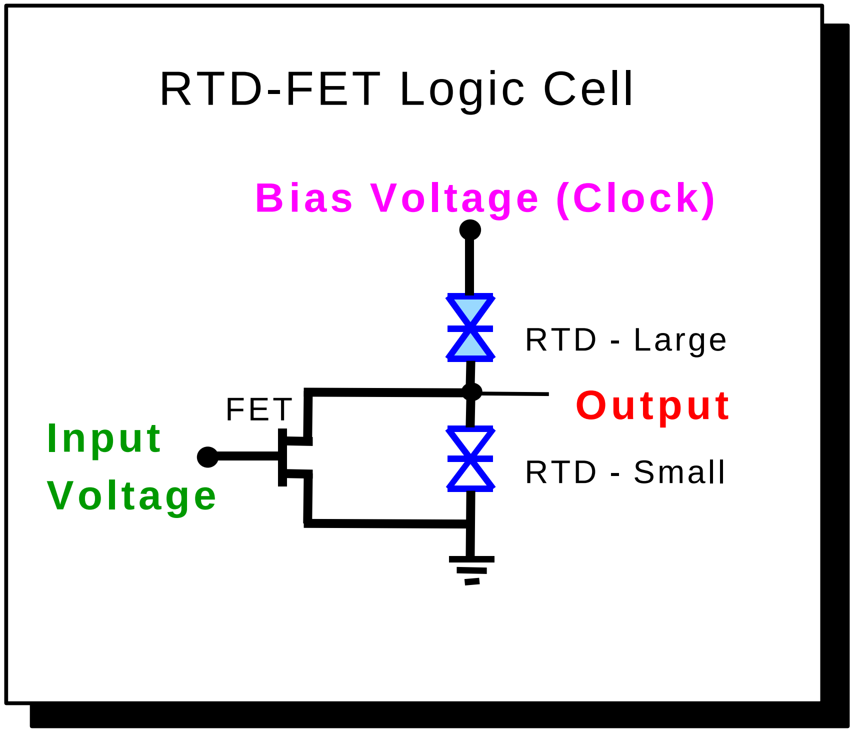


Same functionality with lower component count

RTD - GMR Hybrid

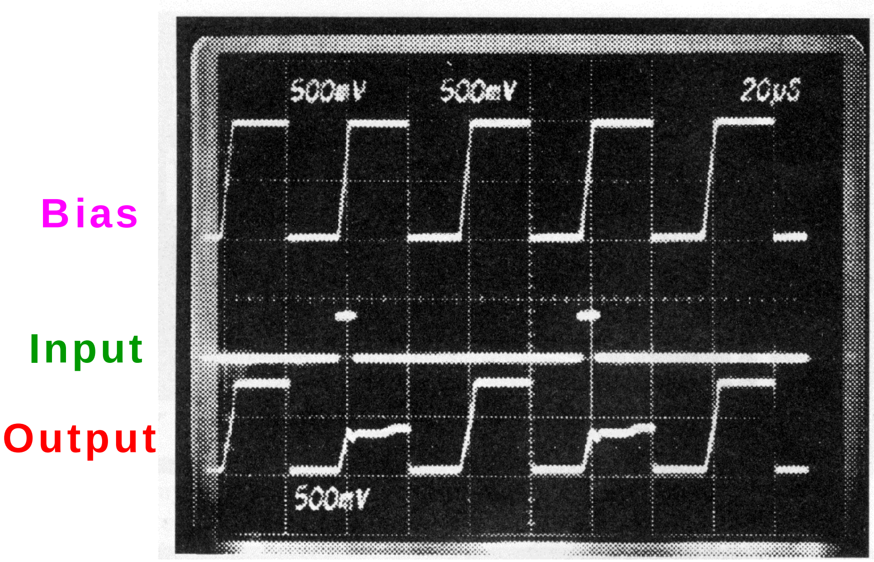
MOnostable-BIstable Logic Element – MOBILE

Maezawa & Mizutani (1993)

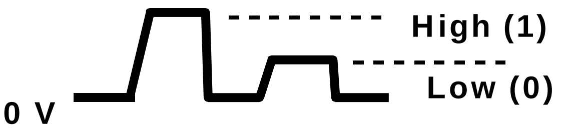


MOBILE INVERTER

Chen *et al*, IEEE Elec. Device Lett. 16, 70 (1995)

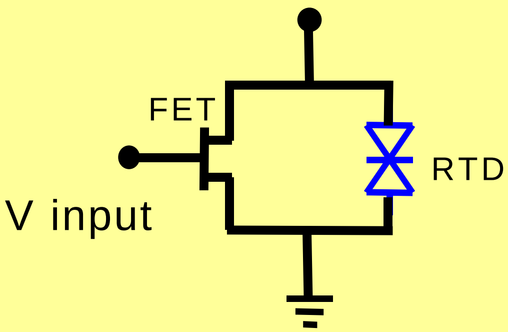


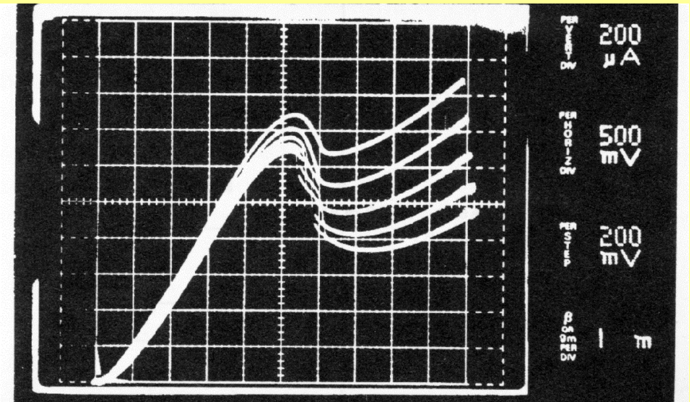
Fast, low component count cell for logic, digital signal processing



RTD - GMR Hybrid: Parallel Combination

FET gate voltage controls circuit: VOLATILE

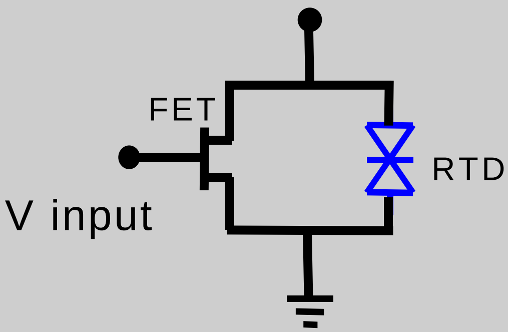


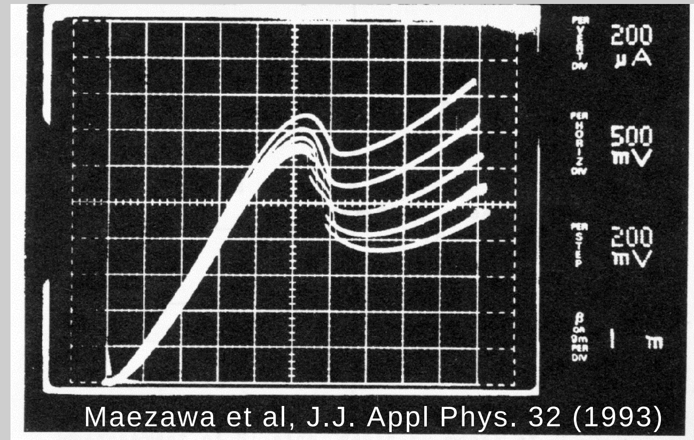


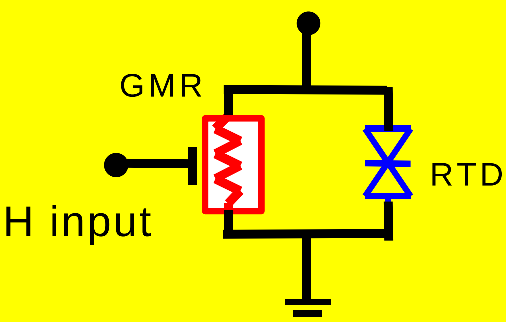
Maezawa et al, J.J. Appl Phys. 32 (1993)

RTD - GMR Hybrid: Parallel Combination

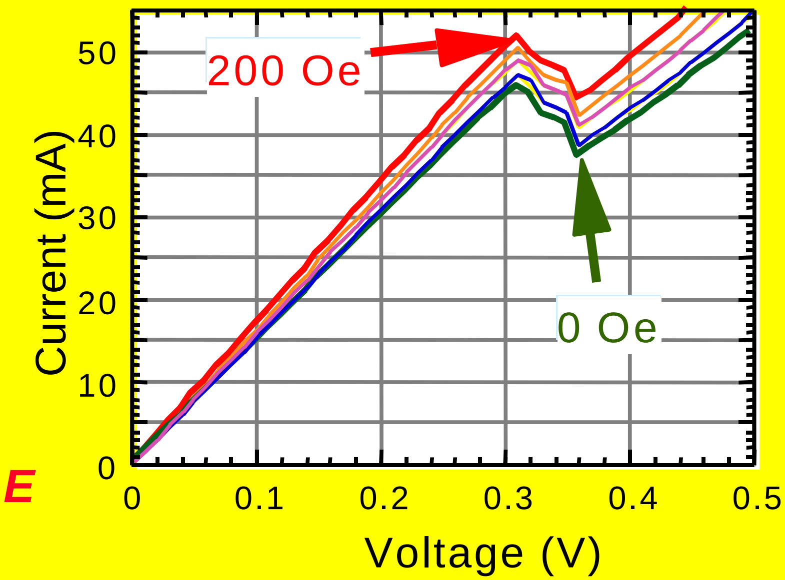
FET gate voltage controls circuit: VOLATILE







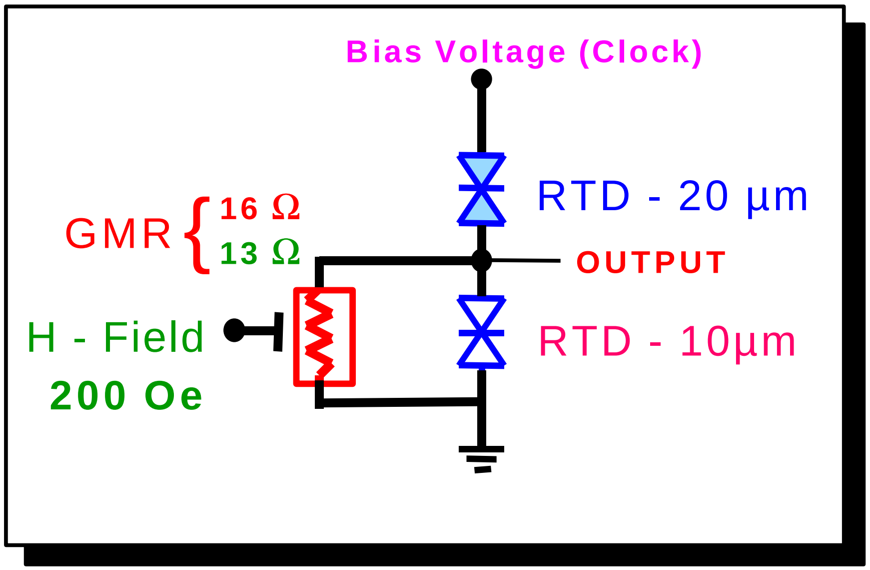
Control **Switching Current**



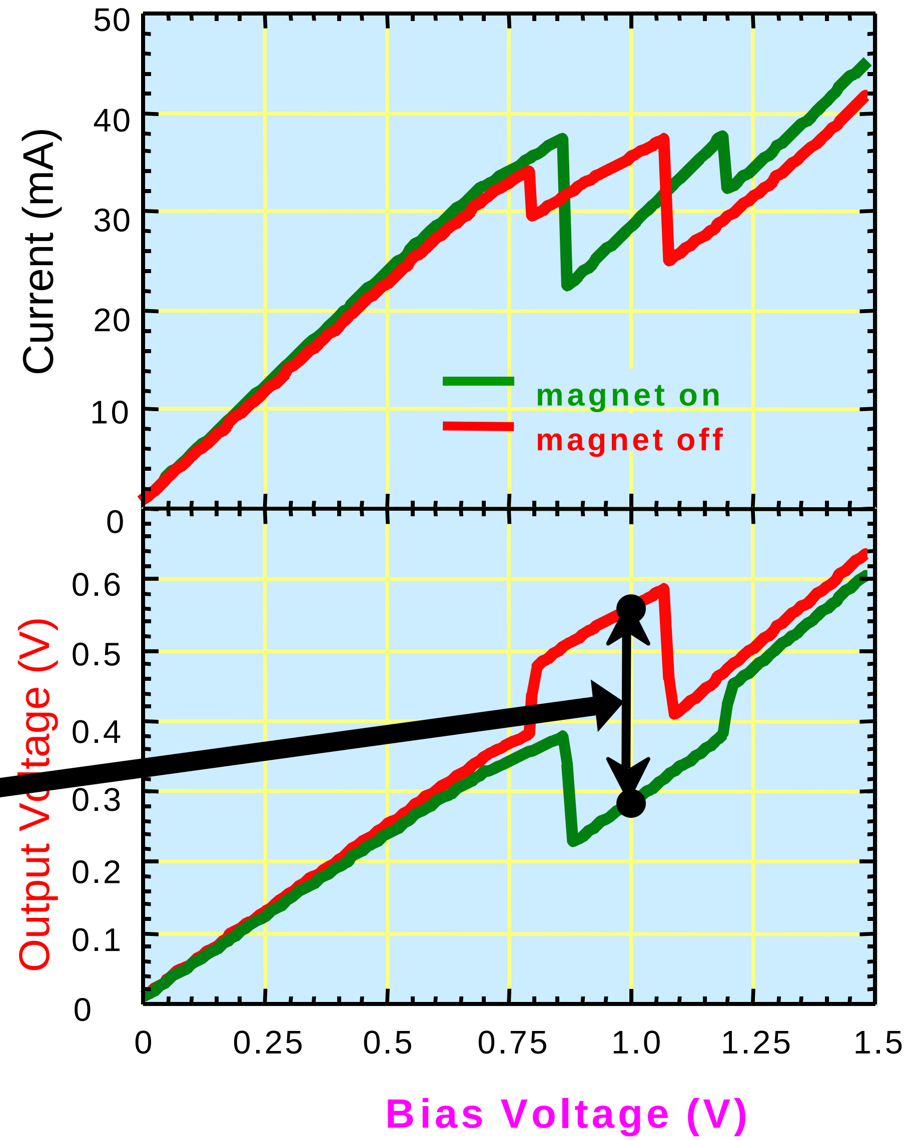
GMR controls circuit: *NONVOLATILE*

RTD - GMR Hybrid: Parallel Combination

MOBILE: DC Limit



2 logic levels clearly defined



State of **GMR** CONTROLS which **RTD** switches first

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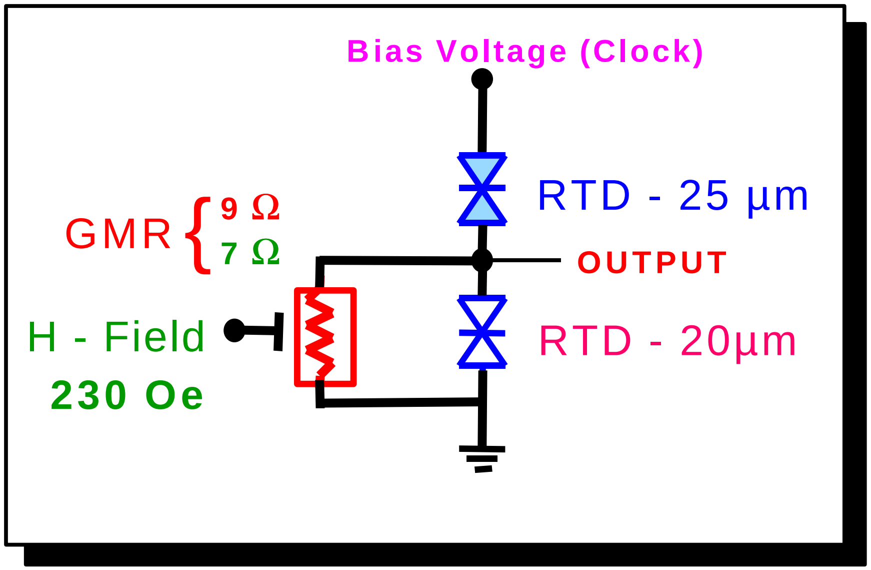
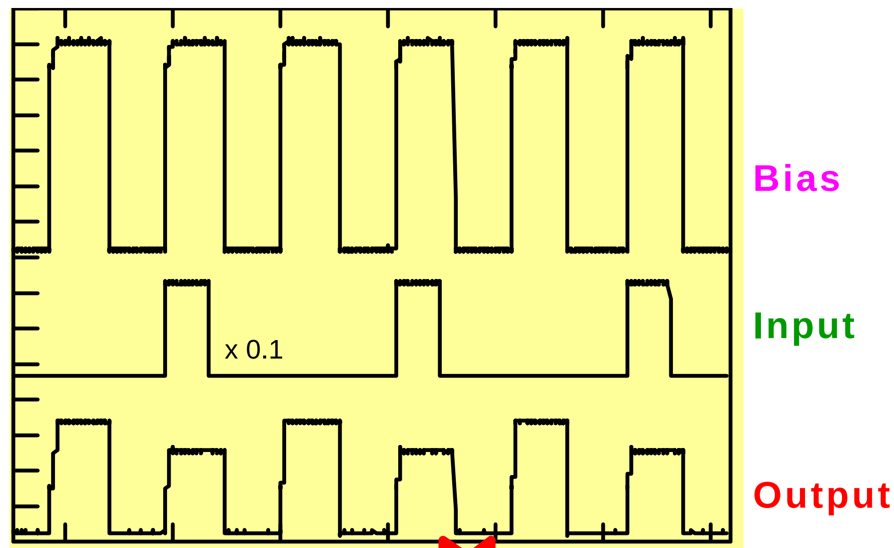
RTD - GMR Hybrid: Parallel Combination

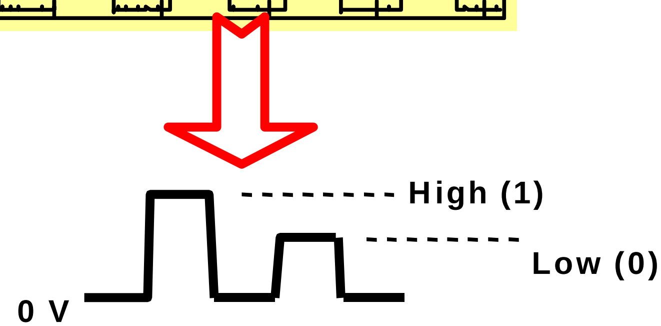
MOBILE: AC Operation

Clock Frequency: 1.0 kHz
Bias Voltage: 1.3 V
Pulsed H: 230 Oe
Output Signal: 0.7 V - H off
0.4 V - H on



MOBILE INVERTER





Duplicates function of standard MOBILE

plus

***Nonvolatile programmable* inverter**

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RTD - GMR Spintronic Devices

- **Hybrid circuits constructed**
  - MBE grown AlSb/GaSb/AlSb RiTDs
  - Co/Cu Multilayer GMRs
- ***NonVolatile* control of RTD**
  - Switching Current
  - Digital Voltage States
- **MOBILE Inverter Operation**
  - DC Limit
  - Clocked Operation

Hanbicki et al, *Applied Phys. Lett*. 79, 20 August 2001

Semiconductor Spintronic Devices

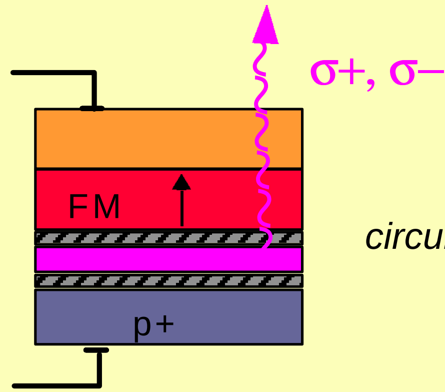
Quantum Spin Electronics

Motivation

- Spin as new degree of freedom in quantum device structures
- Combine *nonvolatile character* with *band gap engineering*
  ⇨ *new functionality*

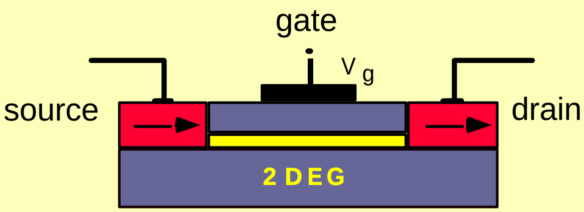
Applications / Payoff

- Tunable / polarized optoelectronics
  quantum info transfer, sensing,
  integrated optical isolators
- Nonvolatile programmable logic
- Magnetic devices with *gain*
- System-on-a-chip



spin-LED

circularly polarized output

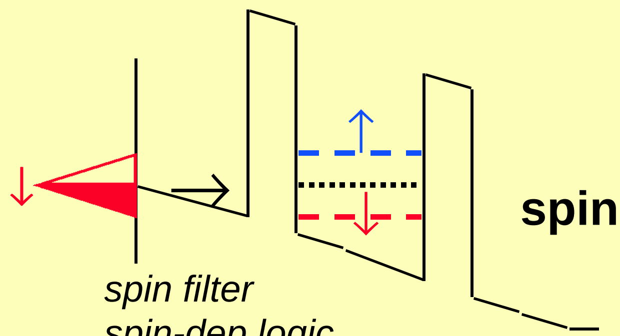


spin-FET

single transistor
nonvolatile memory

2DEG transport

M = 4th terminal



spin-RTDs

spin filter
spin-dep logic
gated RTD

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Semiconductor Spintronics

Essential Requirements for *SpinS* Technology

(i) efficient **electrical injection** of spin-polarized carriers

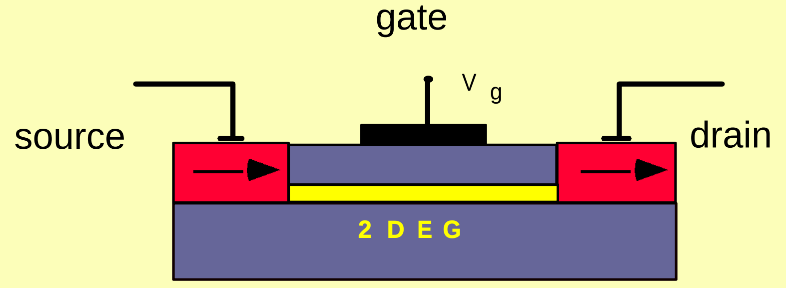
(ii) efficient spin **transport** within host medium

(iii) effective **control / manipulation** for desired functionality

(iv) effective **detection** of spin-polarized carriers

spin-FET

nonvolatile prog transistor
M = 4th terminal
GAIN

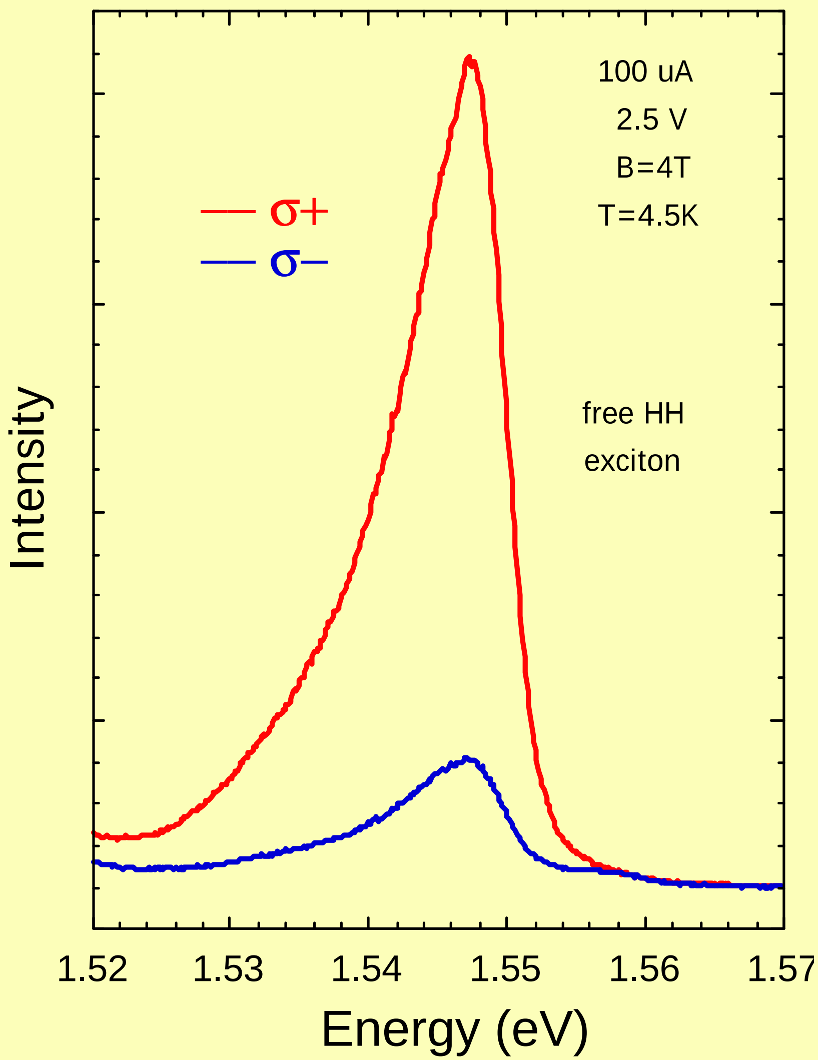


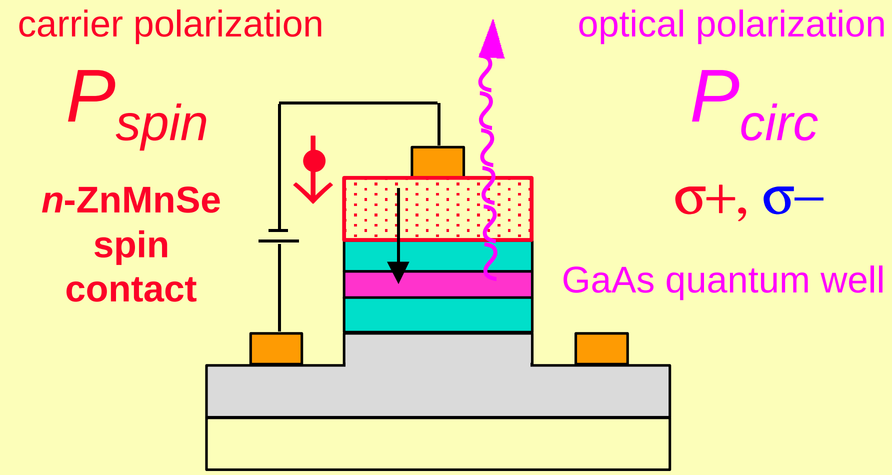
2DEG transport

Datta and Das (1990)

Demonstrate & *Quantify* Electrical Spin Injection

ZnMnSe / AlGaAs spin-LED





$$P_{spin} = P_{circ} > 85\ \%$$

- **Highly efficient (> 85%) elec. spin injection demonstrated**
- **The spin-LED provides the *only***
  quantitative
  model independent
  measure of elec. spin injection

Jonker et al, PRB 62, 8180 (2000)

Semiconductor Spintronics

Essential Requirements for *SpinS* Technology

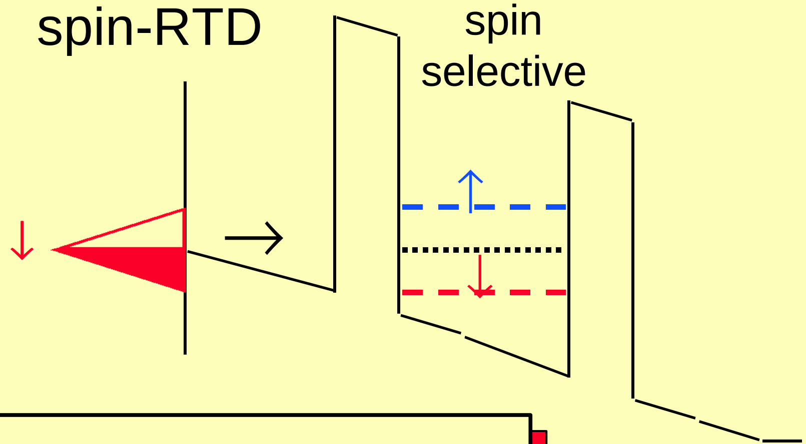
(i) efficient **electrical injection** of spin-polarized carriers

(ii) efficient spin **transport** within host medium

(iii) **effective control / manipulation for desired functionality**

(iv) effective **detection** of spin-polarized carriers

spin-RTD



gated RTD (3 terminal) with *GAIN*

- Need ferromagnetic semi QW
- All existing ones are p-type
- Electrons strongly preferred
  long spin lifetime
  high speed devices

6.1 Å materials offer an avenue

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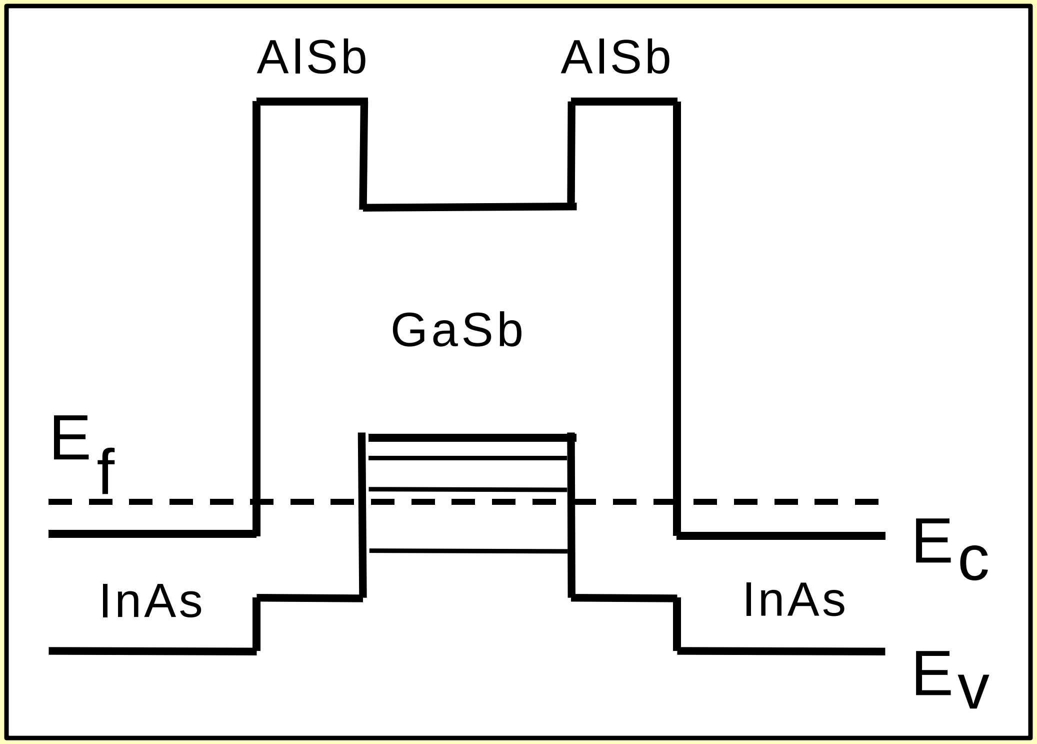
Resonant *Interband* Tunneling Diode



Electrons tunnel through *valence band states* of quantum well

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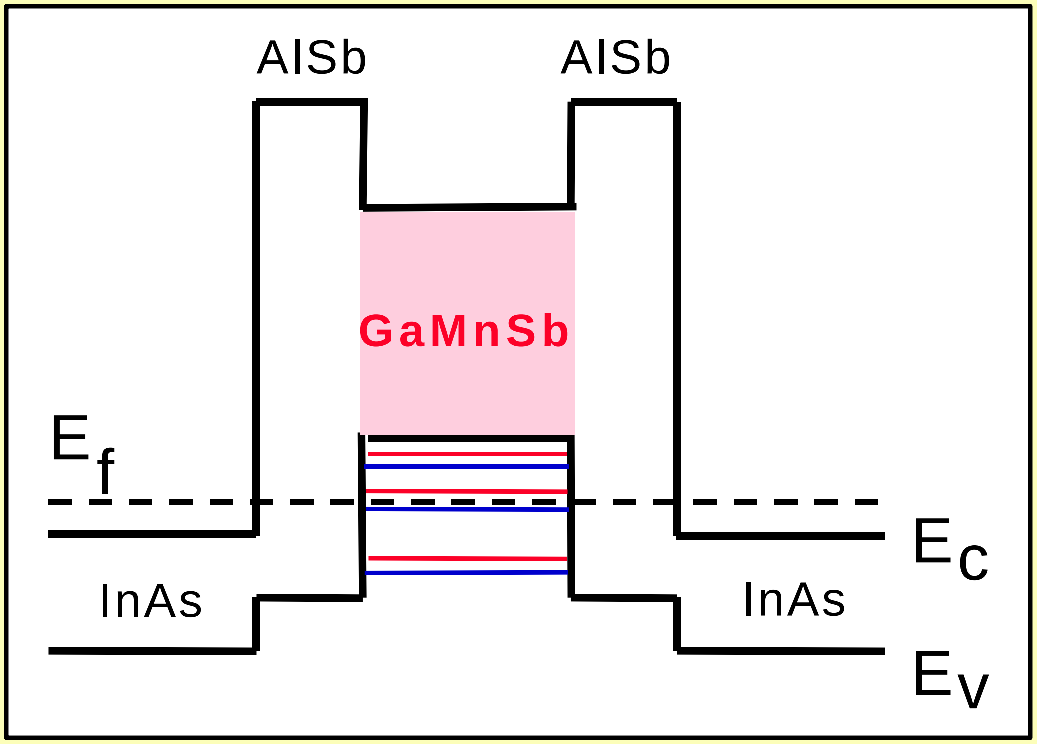
Resonant *Interband* Tunneling Diode



Ferromagnetic
Semiconductor
p - GaMnSb

Electrons tunnel through ***SPIN-POLARIZED*** valence band states of quantum well

- bias dependent spin-polarized source
- gated RITD (with polarized emitter)

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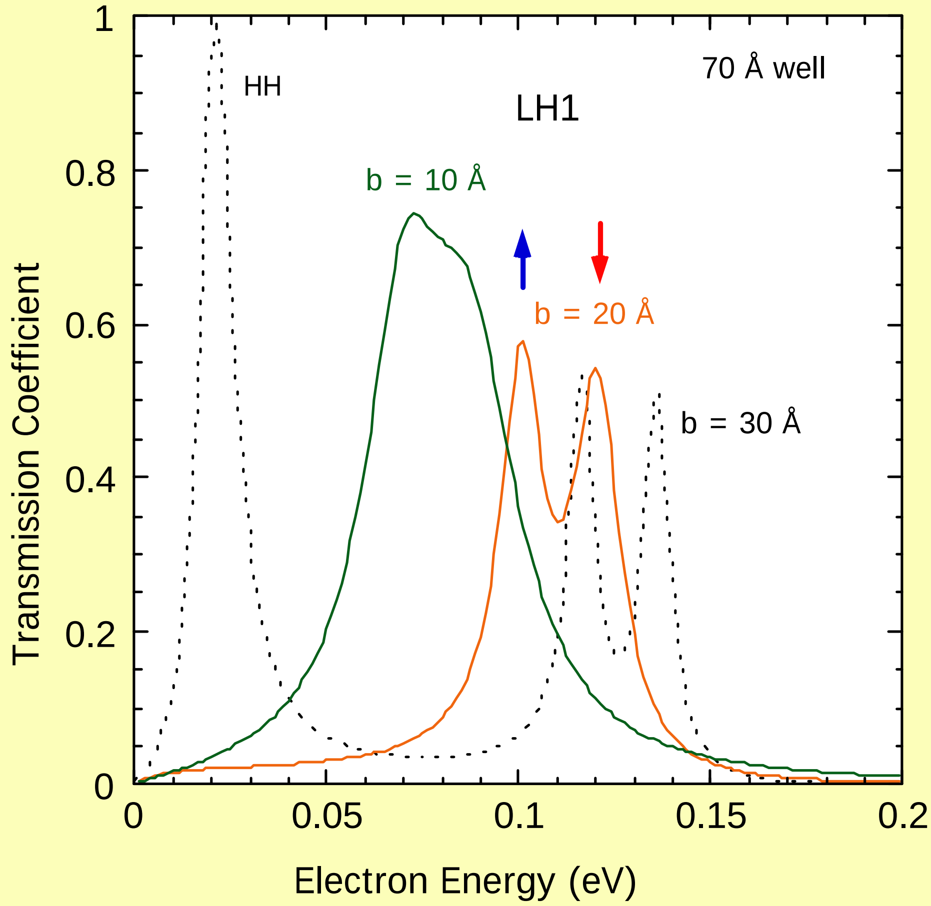
spin-RITD: InAs / AlSb / 70 Å GaMnSb / AlSb / InAs

effect of barrier width - b



Transmission coefficients
calculated in 8-band k.p
<u>M</u> perpendicular

LH spin splitting = 30 meV bzc
conservative estimate
based on GaMnAs (Ohno)
spin = ± 1/2

Spin-splitting of LH best resolved for wider barriers
- critical design parameter

Andre Petukhov

all model calculations

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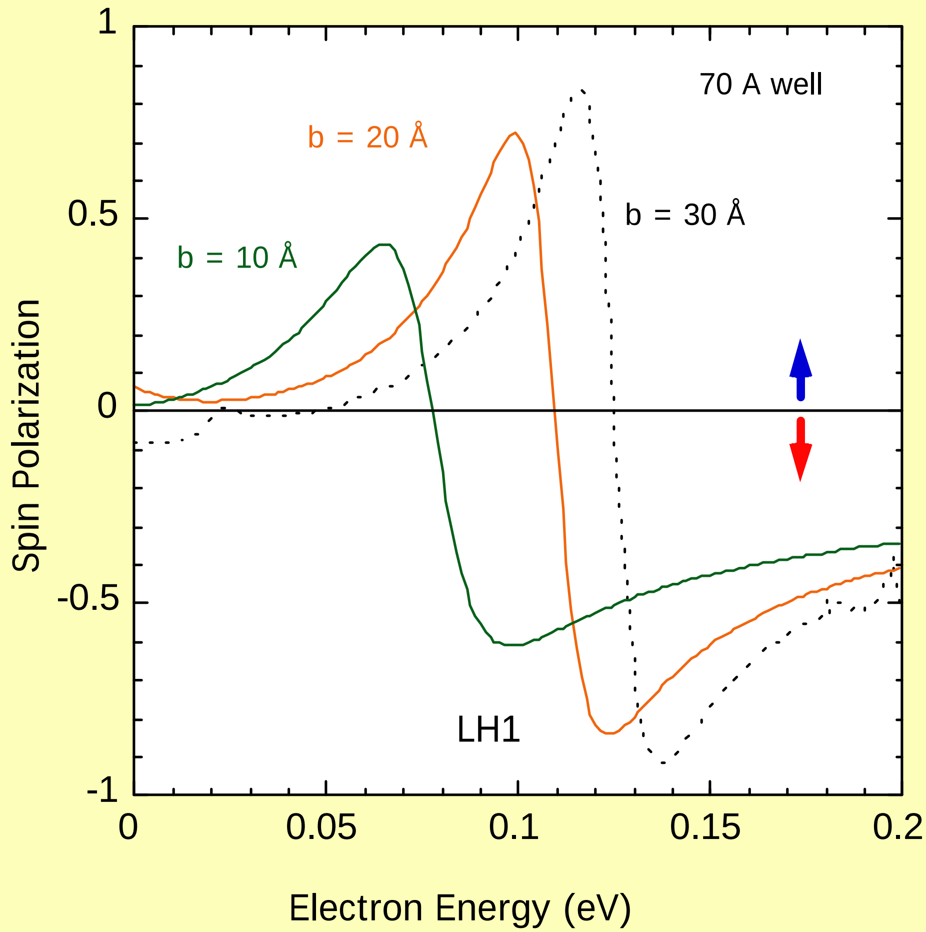
spin-RITD: InAs / AlSb / 70 Å GaMnSb / AlSb / InAs

effect of barrier width - b



Transmission coefficients calculated in 8-band k.p
M perpendicular

LH spin splitting = 30 meV
conservative estimate
based on GaMnAs (Ohno)

Spin-splitting of LH best resolved for wider barriers

Spin polarization
for different barrier widths

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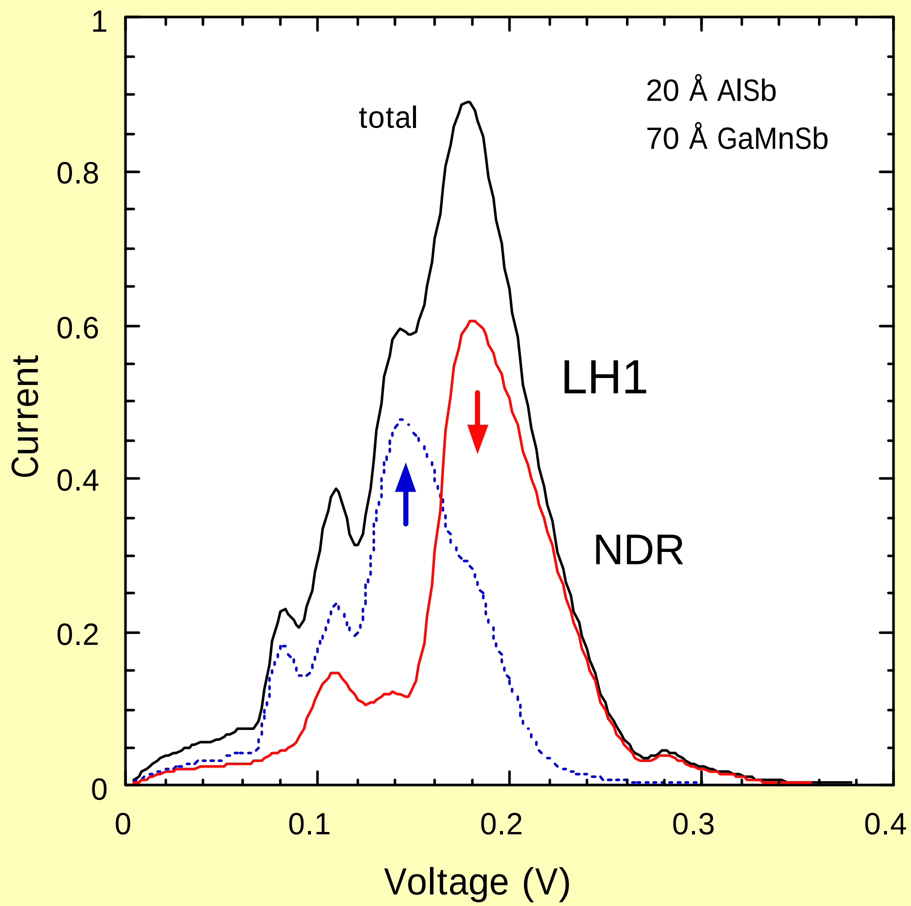
spin-RITD: InAs / AlSb / 70 Å GaMnSb / AlSb / InAs

20 Å AlSb barriers



I-V characteristic

spin-resolved transport

M perpendicular

LH spin splitting = 30 meV

conservative estimate

E_F = 0.04 eV (n ~ 10^{18} cm^{-3})

integrated over k-parallel

Probably naïve to simply look for spin-split features

Must do polarization analysis

NB: other effects may narrow peaks

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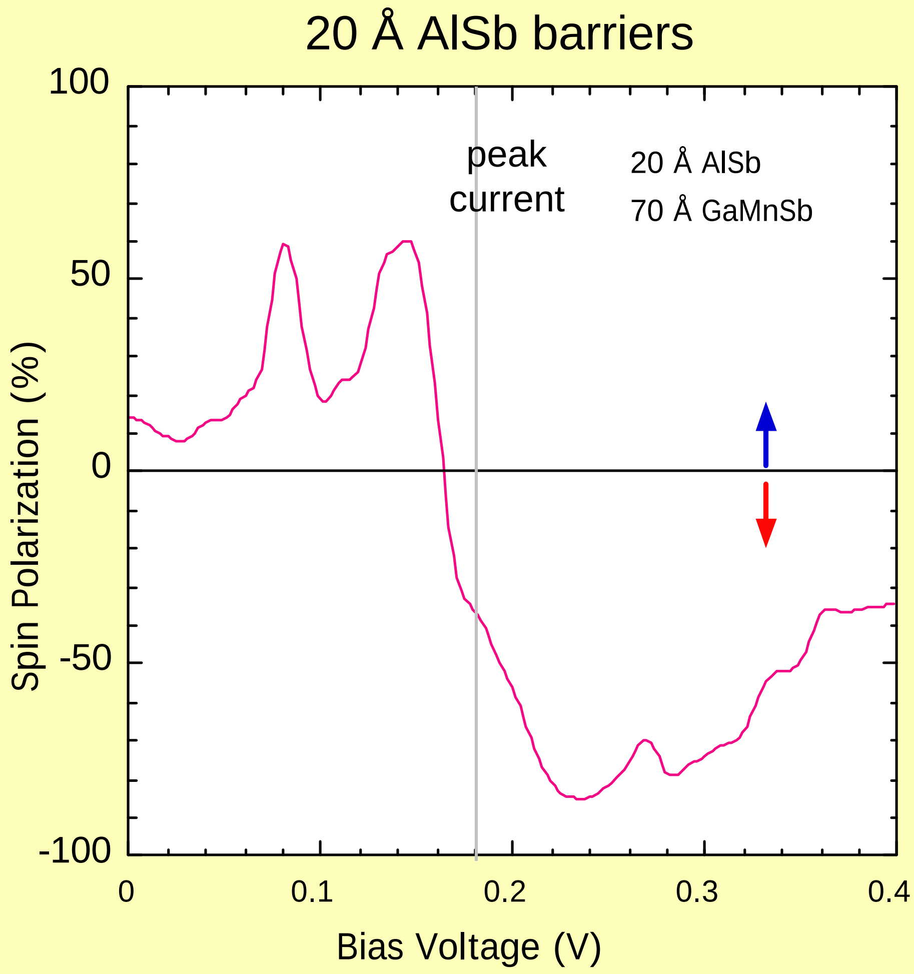
spin-RITD: InAs / AlSb / 70 Å GaMnSb / AlSb / InAs



Spin polarization of I

bi-polar(ization)

M perpendicular

LH spin splitting = 30 meV

conservative estimate

$E_F = 0.04$ ($n \sim 10^{18}$ cm^{-3})

integrated over k-parallel

Can significantly modulate polarization in both magnitude and sign

RITD switching effects range

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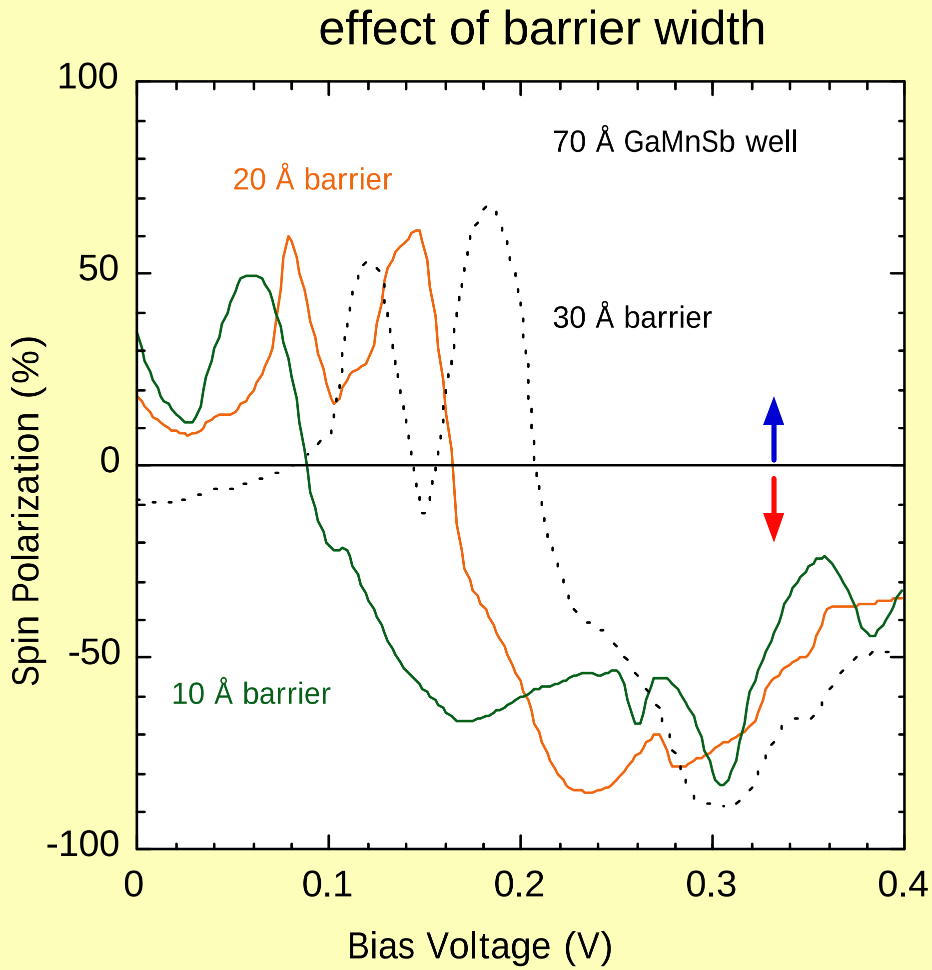
Semiconductor Spintronics

spin-RITD: InAs / AlSb / 70 Å GaMnSb / AlSb / InAs



Spin polarization of I

bi-polar(ization)

M perpendicular

LH spin splitting = 30 meV

conservative estimate

E_F = 0.04 (n ~ 10^{18} cm^{-3})

integrated over k-parallel

Can significantly modulate polarization in both magnitude and sign

weak dep on barrier width

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Semiconductor Spintronics

SUMMARY

- Hybrid 6.1 Å RTD / GMR structures: ***building block*** for nonvolatile, reprogrammable logic, memory
- Requirements for semiconductor spintronic devices show very encouraging progress
- 6.1 Å materials / structures offer great opportunity for spin-polarized operation

spin-RITD: InAs / AlSb / GaMnSb / AlSb / InAs

- bias dependent spin-polarized current source
- gated RTD (spin = 3rd terminal)

- Status GaMnSb: tough material to grow (clustering)

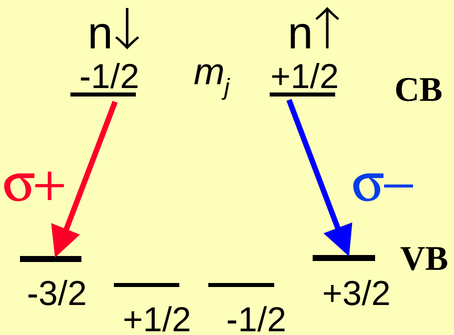
Demonstrate & *Quantify* Electrical Spin Injection

- **Use quantum well *spin-LED* to measure electrical spin injection**

  US patent 5,874,749 for spin-LED (NRL)
- **Spin polarized contact / carriers**

  electrically injected --> radiatively recombine
- **Quantum selection rules provide analytic relationship** P_{circ} ” P_{spin}

$\Delta m_j = \pm 1$



measure optical polarization

obtain spin polarization

$$P_{circ} = \frac{I(\sigma+) - I(\sigma-)}{I(\sigma+) + I(\sigma-)} = \frac{n\downarrow - n\uparrow}{n\downarrow + n\uparrow} = P_{spin}$$

carrier polarization

P_{spin}

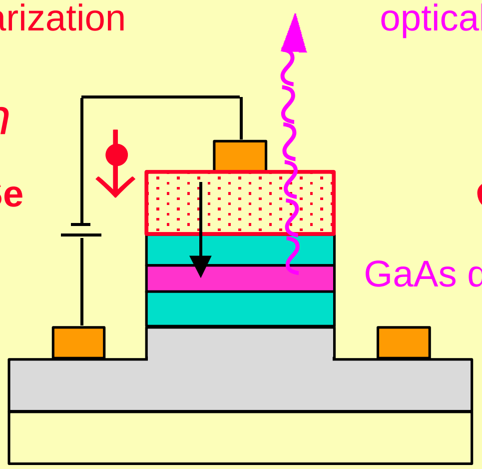
***n*-ZnMnSe spin contact**

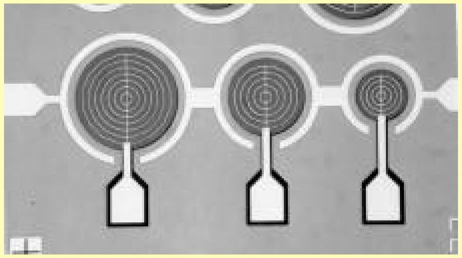
optical polarization

P_{circ}

σ+, σ−

GaAs quantum well





processed LED structures

$$P_{spin} = P_{circ}$$

Quantitative model independent

measure of spin injection

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NRL Epi-Center: facilities used in new RO

Basis of DARPA and ONR funding