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classical and quantum spin devices: theoretical perspectives

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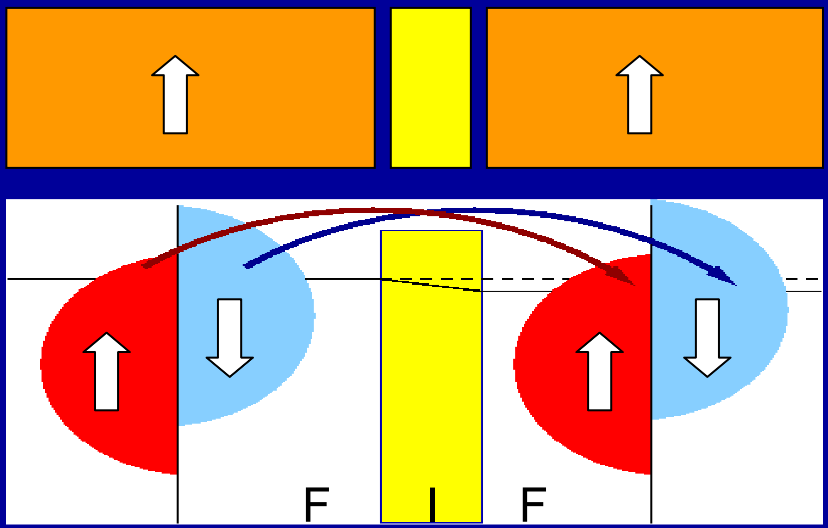
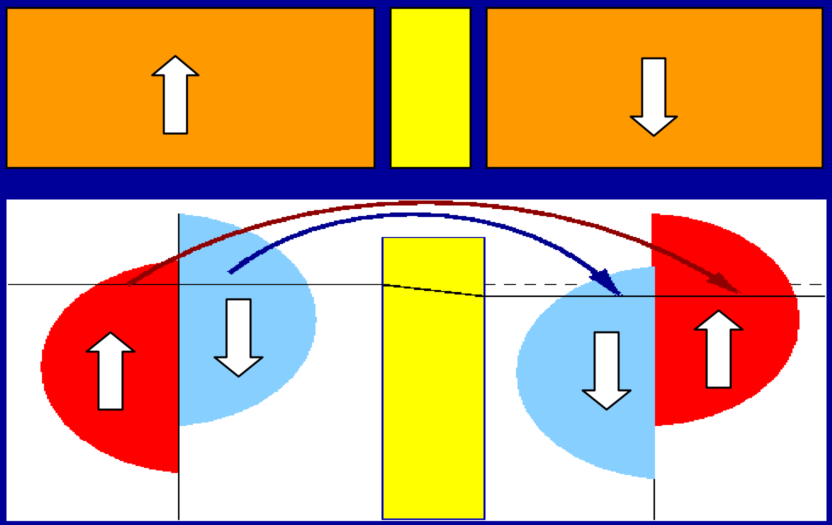
:outline:

- spintronics success story: metal-based devices
- key concepts: spin injection and detection, spin relaxation
- bipolar spintronics: selected novel phenomena
- magnetic bipolar transistors
- spin-to-charge conversion in coupled quantum dots
- entanglement distillation by adiabatic passage (EDAP)
- conclusions: challenges

Tunnel MagnetoResistance

Julliere 1975; Moodera et al. 1995





small resistance R_P

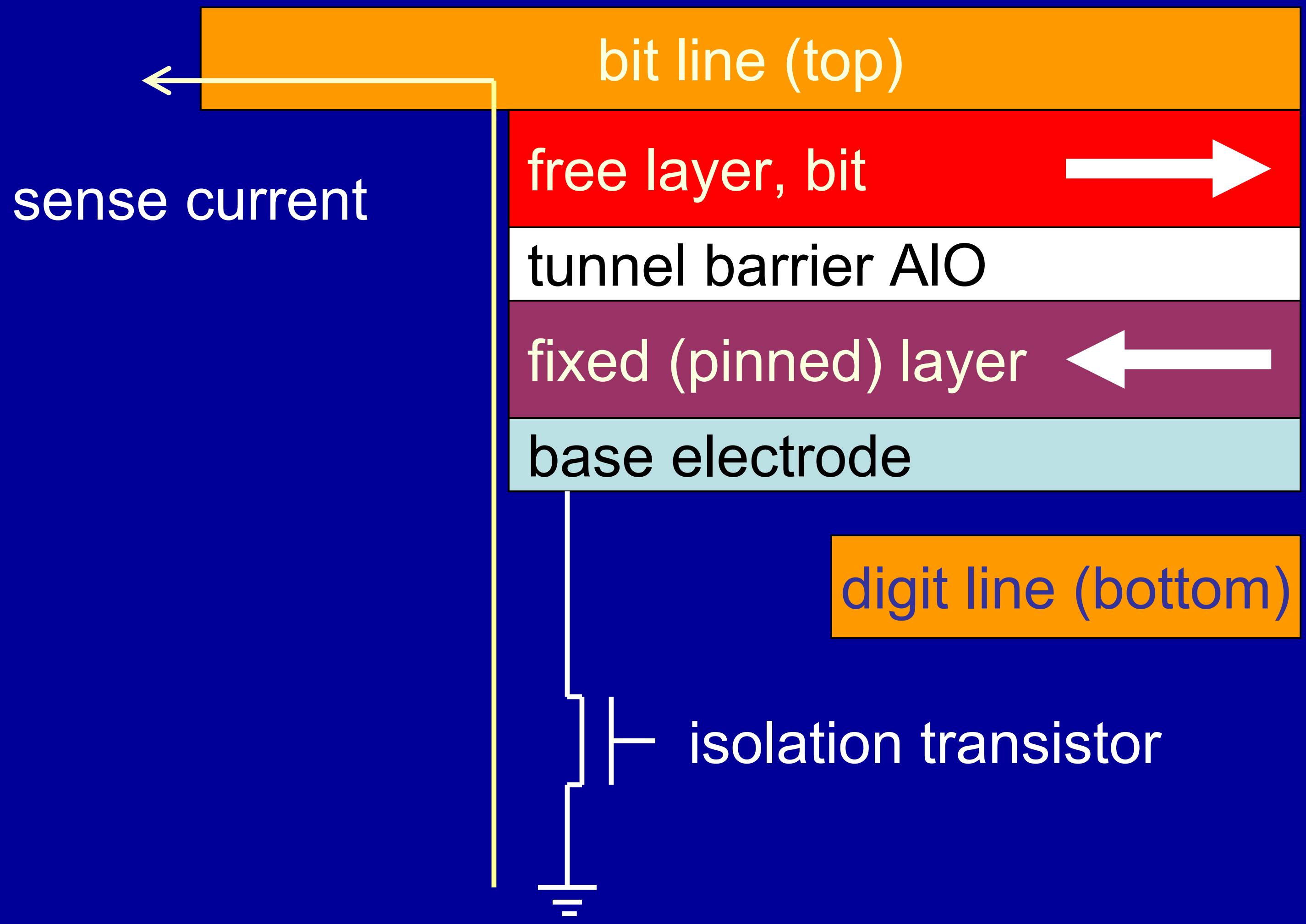
large resistance R_{AP}

$$P = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$$

$$TMR = \frac{R_P - R_{AP}}{R_P} \approx \frac{2P_L P_R}{1 - P_L P_R}$$

TMR about 50-100%

TMR non-volatile MRAM



TMR MRAM vs. CMOS NVRAM

	TMR MRAM	NVRAM
write / erase times	1 ns	10 µs / 1 ms
write / erase energy	10^{-10} J	10^{-7} / 10^{-5} J
durability (cycles)	> 10^{15}	10^{5} – 10^{6}

Source: M. Johnson, J. Phys. Chem. B 109, 14278 (2005)

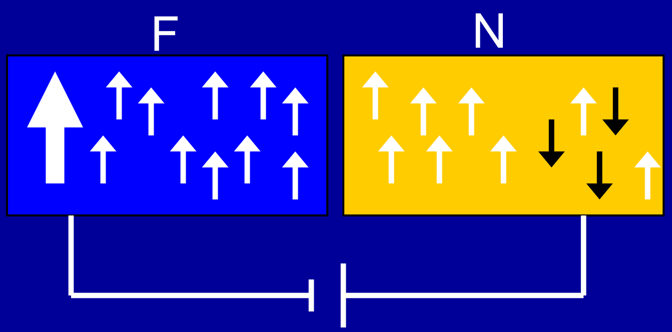
SPINTRONICS GOALS

spin control of electrical properties
(I-V characteristics)

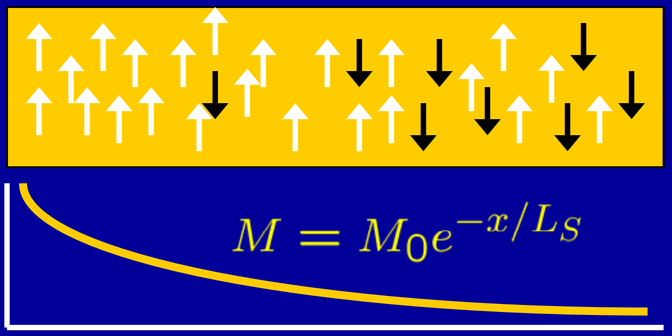
electrical control of spin
(magnetization)

SPINTRONICS' 3 REQUIREMENTS

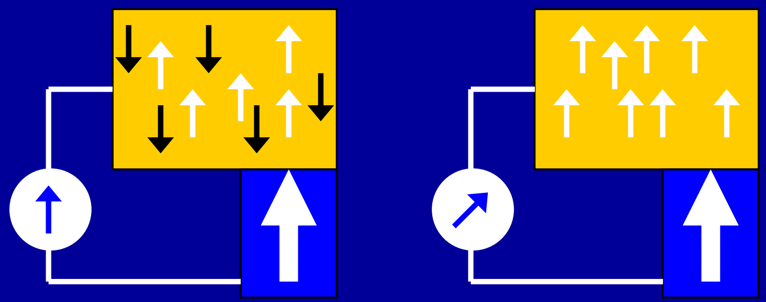
- EFFICIENT SPIN INJECTION



- SLOW SPIN RELAXATION



- RELIABLE SPIN DETECTION

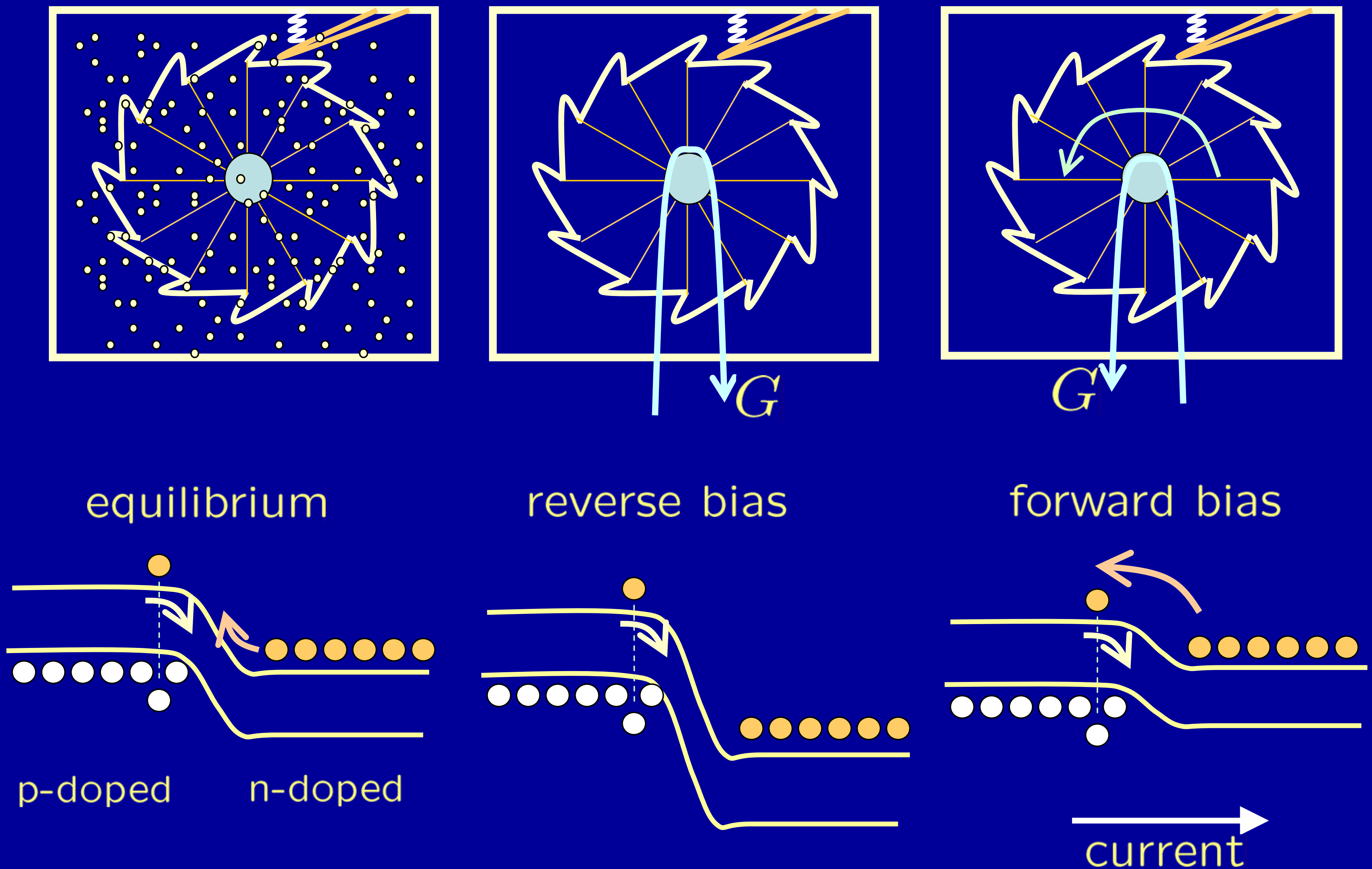


Silsbee-Johnson spin-charge coupling

BIPOLAR SPINTRONICS

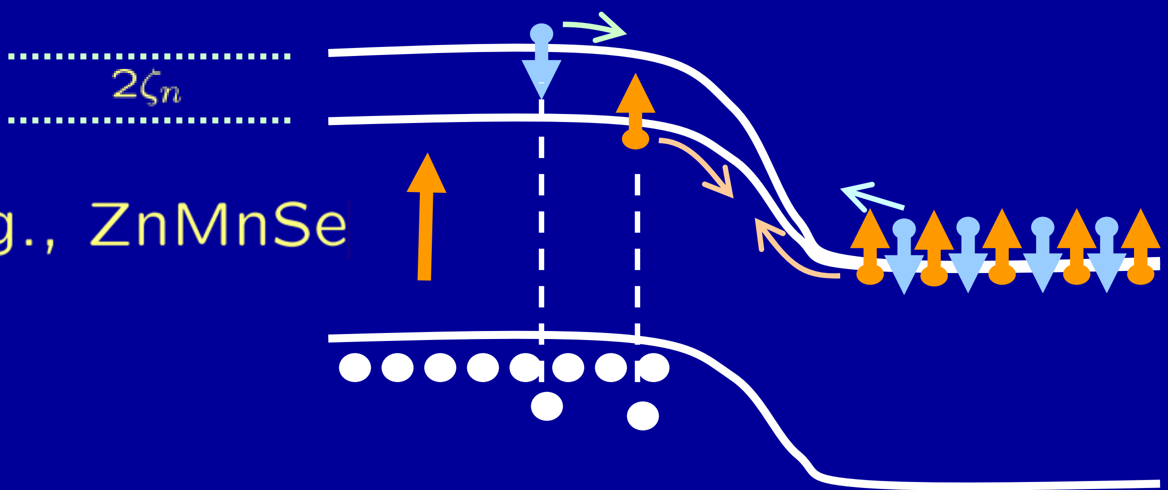
ratchet and paw vs. diode

rectification of rotation vs. current

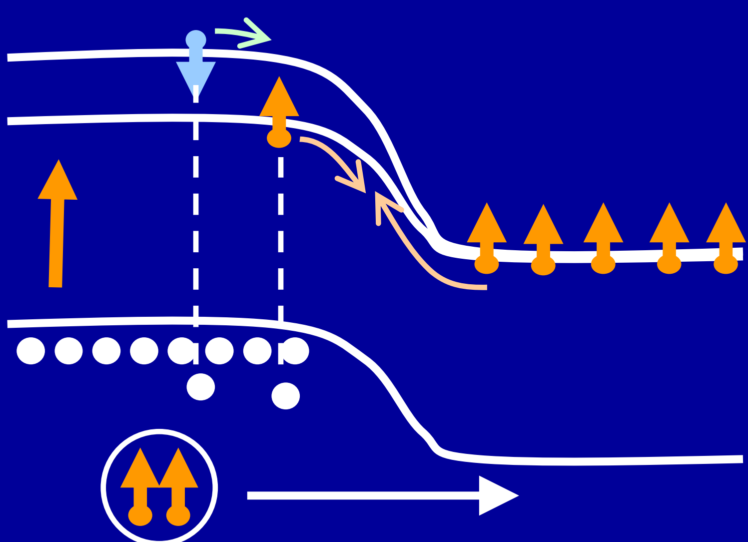


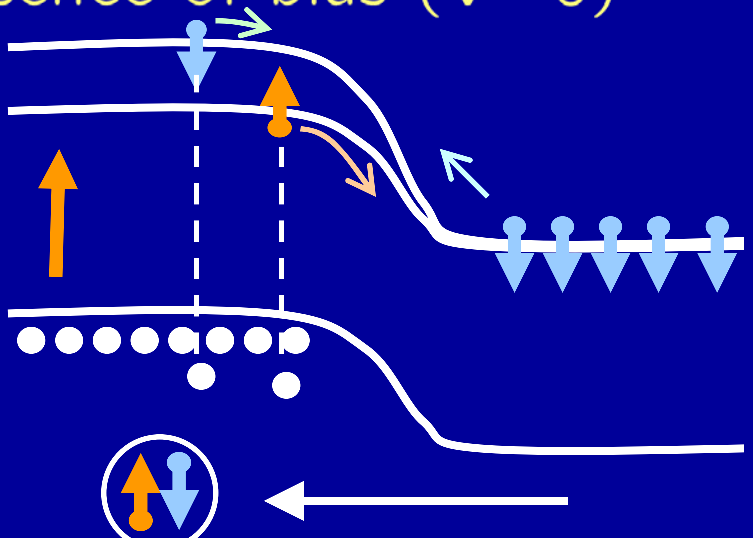
magnetic diode

spin-voltaic effect



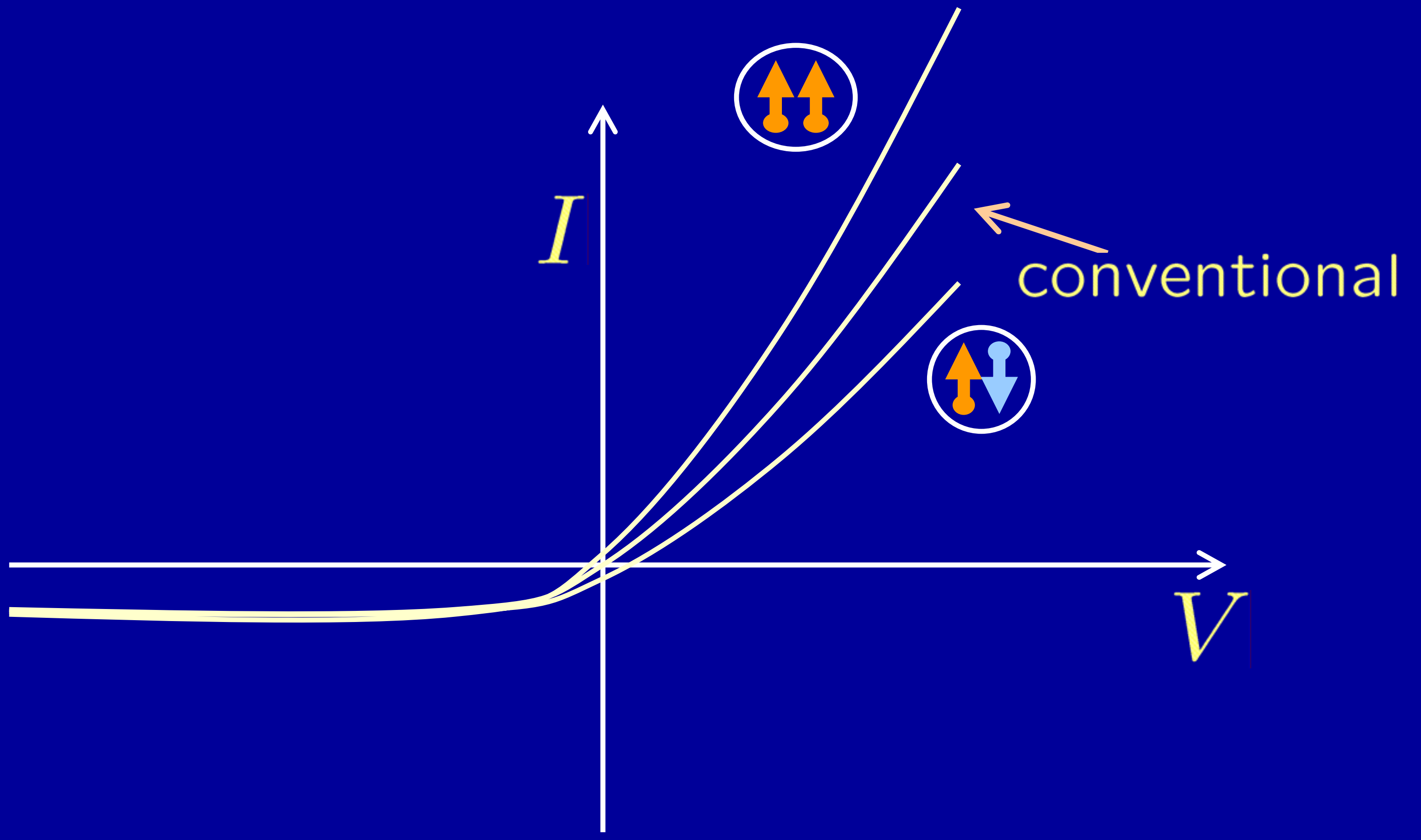
current flows even in absence of bias (V=0)





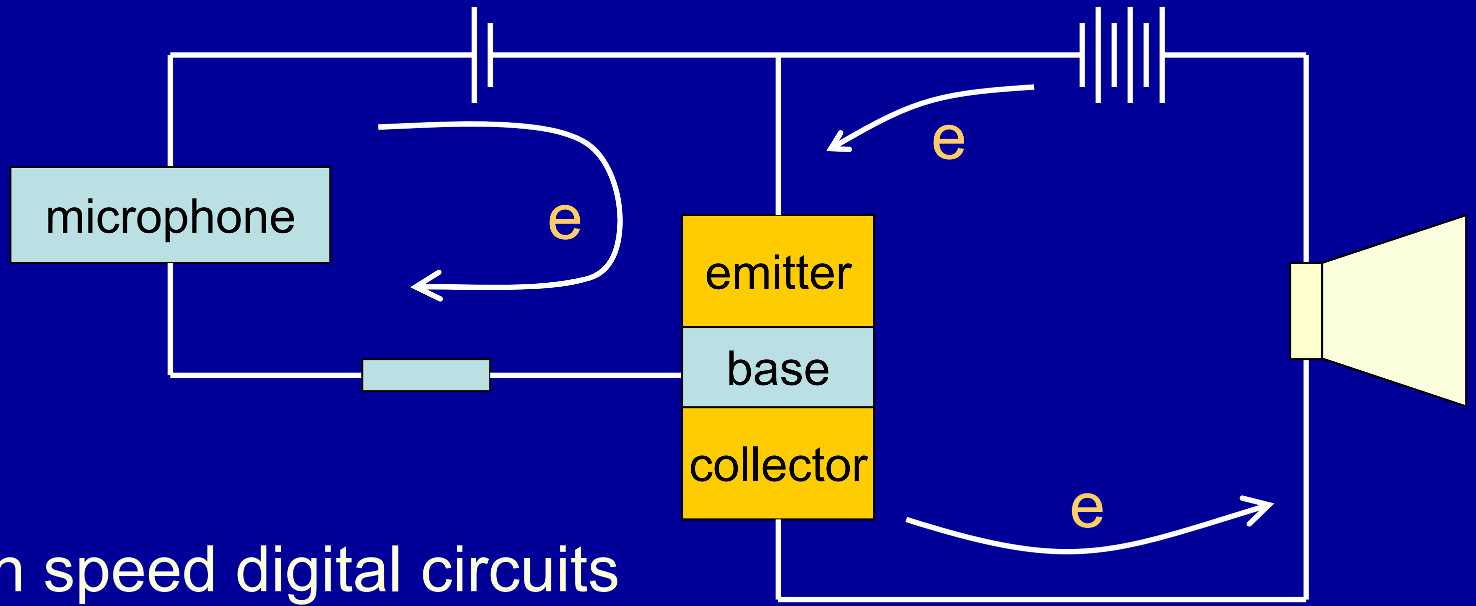
magnetic diode

GMR



$$I = I_0\{e^{eV/k_BT}(1 + \delta P_n \cdot P_p) - 1\}$$

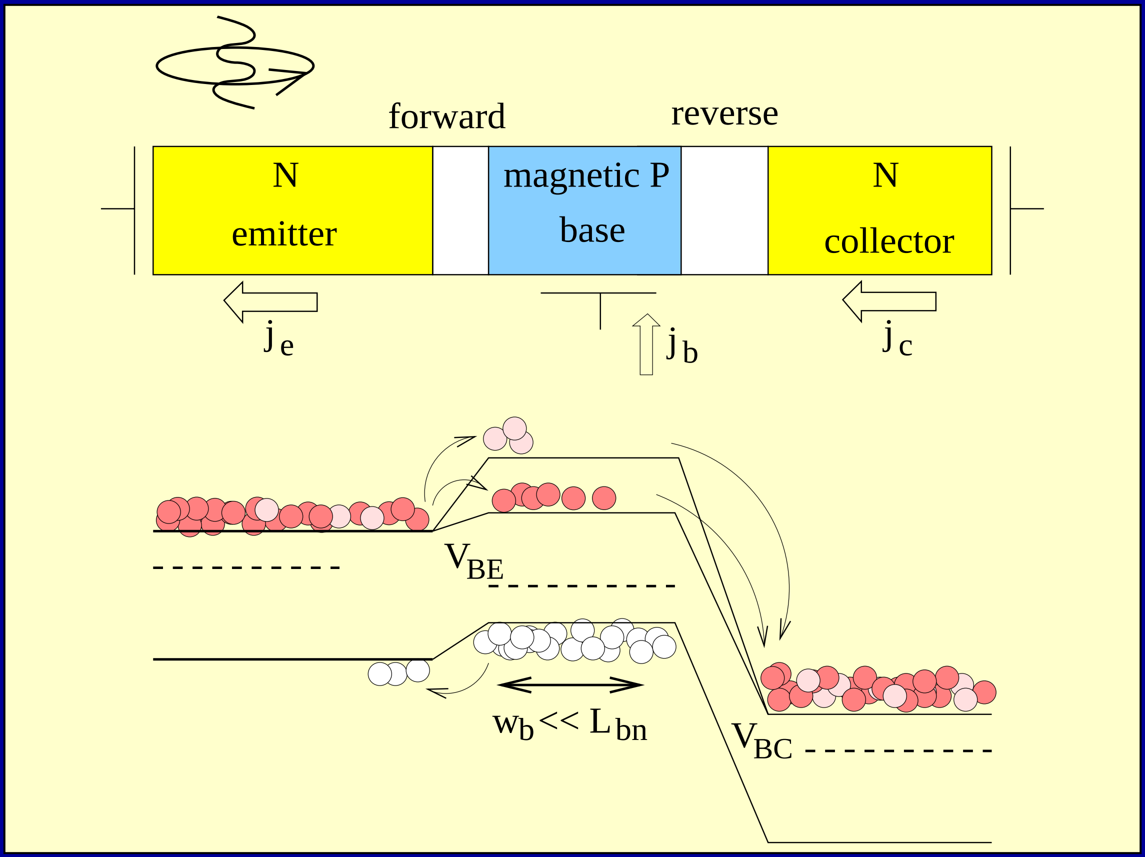
bipolar junction transistor



- High speed digital circuits
- BiCMOS
- Small signal amplification
- High frequency analog circuits (SiGe, GaAs HBTs)
- Integrated Circuits market: 20% BJT, 75% MOSFET

Magnetic bipolar transistor (MBT)

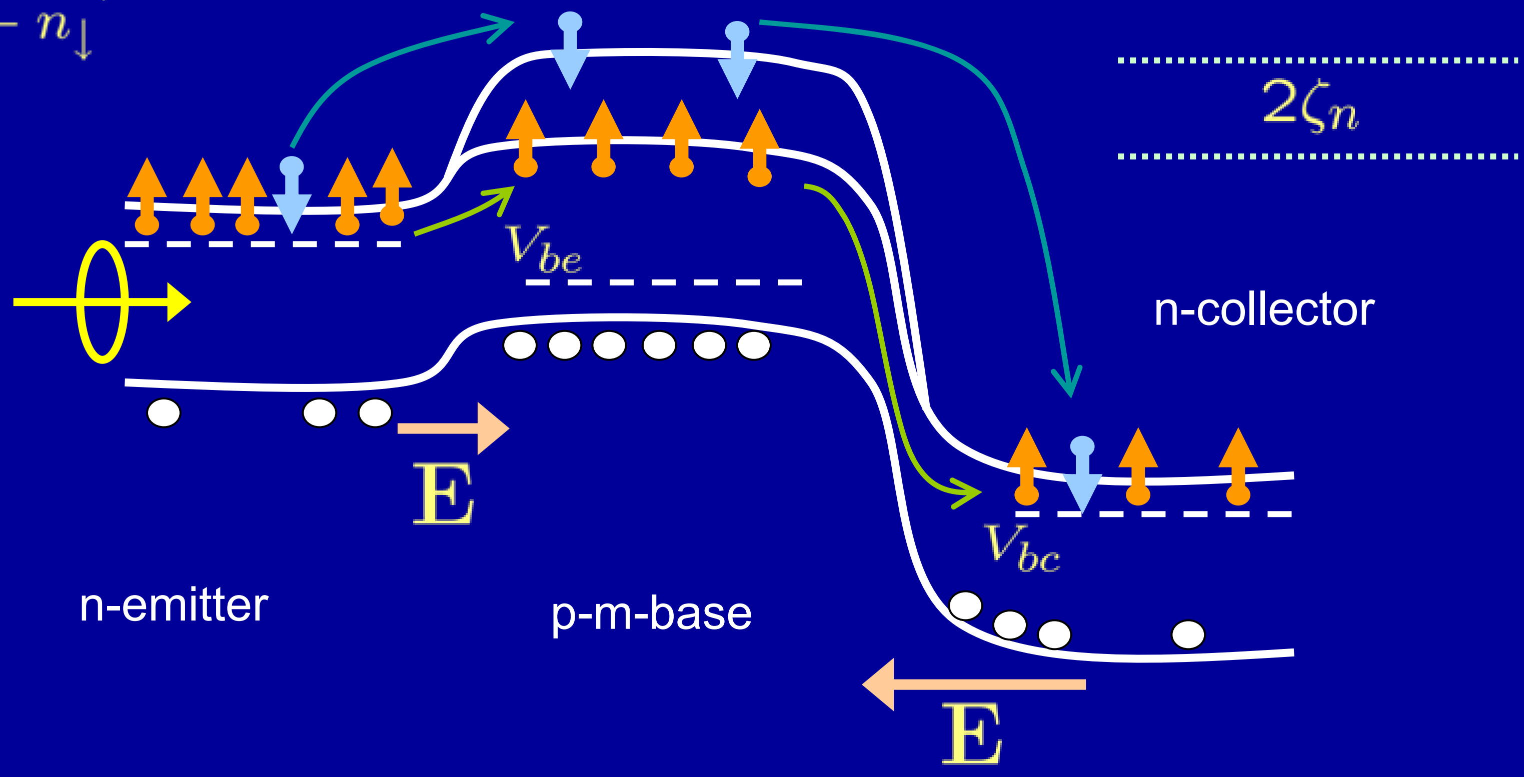
J. Fabian, I. Zutic and S. Das Sarma, cond-mat/0211639; Appl. Phys. Lett. 84, 85 (2004);
J. Fabian and I. Zutic, Phys. Rev. B 69, 115314 (2004).



- all semiconductor
- magnetic semiconductor active region
- versatile design
- materials restricted

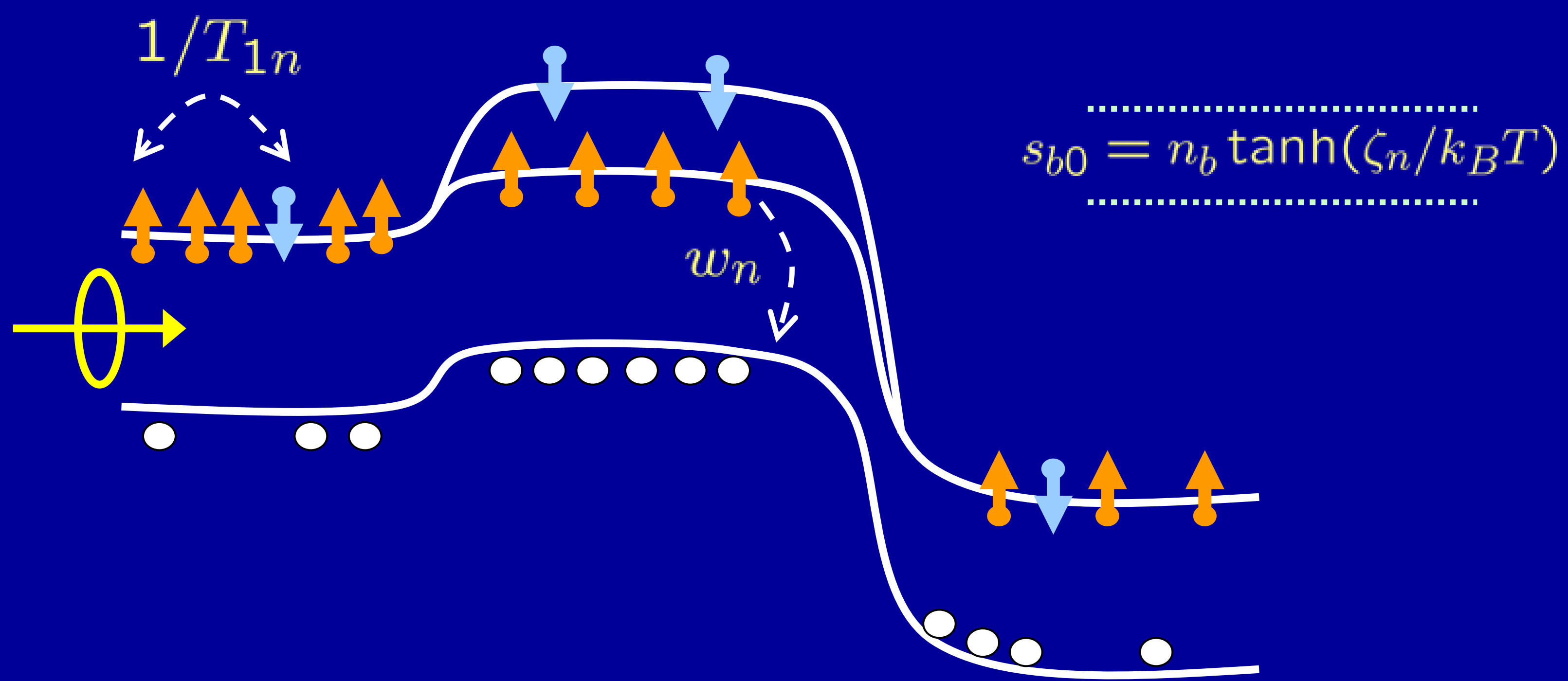
drift-diffusion

$$n = n_\uparrow + n_\downarrow$$
$$s = n_\uparrow - n_\downarrow$$
$$P = \frac{s}{n}$$



$$\begin{aligned}
\mathbf{J}_{n\lambda} &= q\mu_{n\lambda}n_\lambda\mathbf{E} + qD_{n\lambda}\nabla n_\lambda - q\lambda\mu_{n\lambda}n_\lambda\nabla\zeta_n \\
\mathbf{J}_{p\lambda} &= q\mu_{p\lambda}p_\lambda\mathbf{E} - qD_{p\lambda}\nabla p_\lambda - q\lambda\mu_{p\lambda}p_\lambda\nabla\zeta_p
\end{aligned}$$

charge and spin continuity

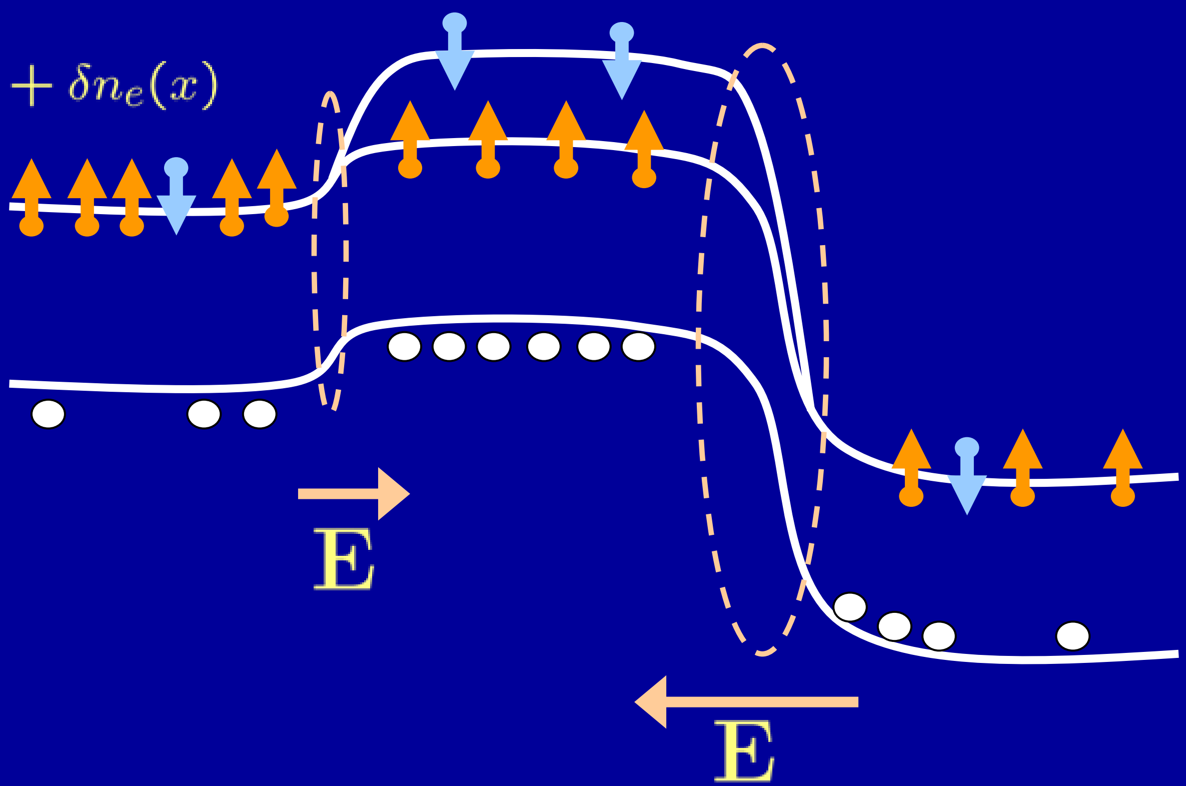


$$\nabla \cdot \frac{\mathbf{J}_{n\lambda}}{q} = +w_{n\lambda}(n_\lambda p - n_{\lambda 0} p_0) + \frac{n_\lambda - n_{-\lambda} - \lambda \tilde{s_n}}{2T_{1n}}$$

$$\nabla \cdot \frac{\mathbf{J}_{p\lambda}}{q} = -w_{p\lambda}(p_\lambda n - p_{\lambda 0} n_0) + \frac{p_\lambda - p_{-\lambda} - \lambda \tilde{s_p}}{2T_{1p}}$$

self-consistency with electrostatics

$$n_e(x) = N_d + \delta n_e(x)$$



$$\nabla \cdot \mathbf{E} = \frac{\rho}{\epsilon}, \quad \rho = q(p - n + N_d - N_a)$$

Analytical modeling

Generalized Shockley theory:

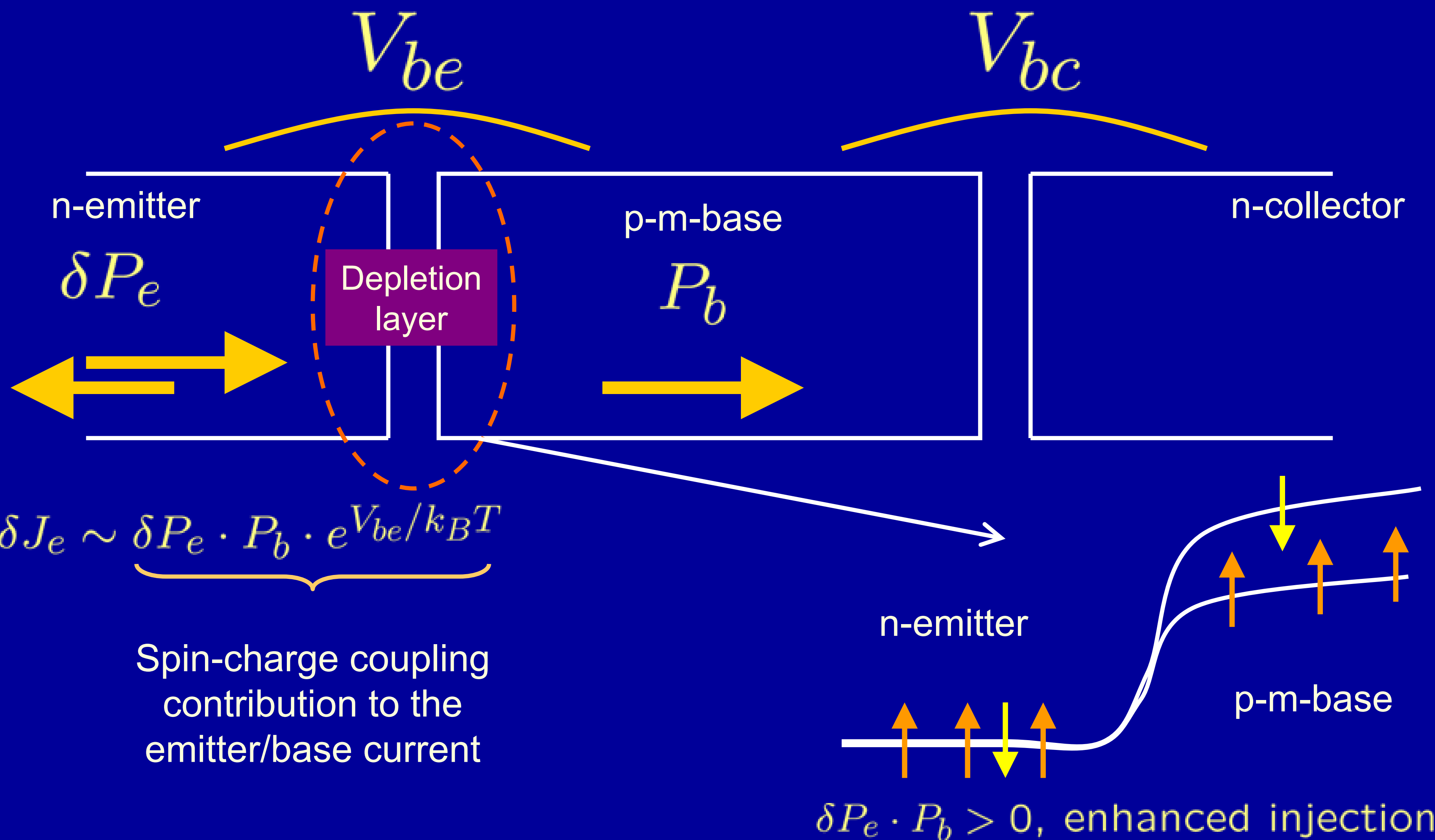
carrier and spin quasiequilibrium in
space-charge regions (constant chemical potentials)

+

continuity of spin current through space-charge regions

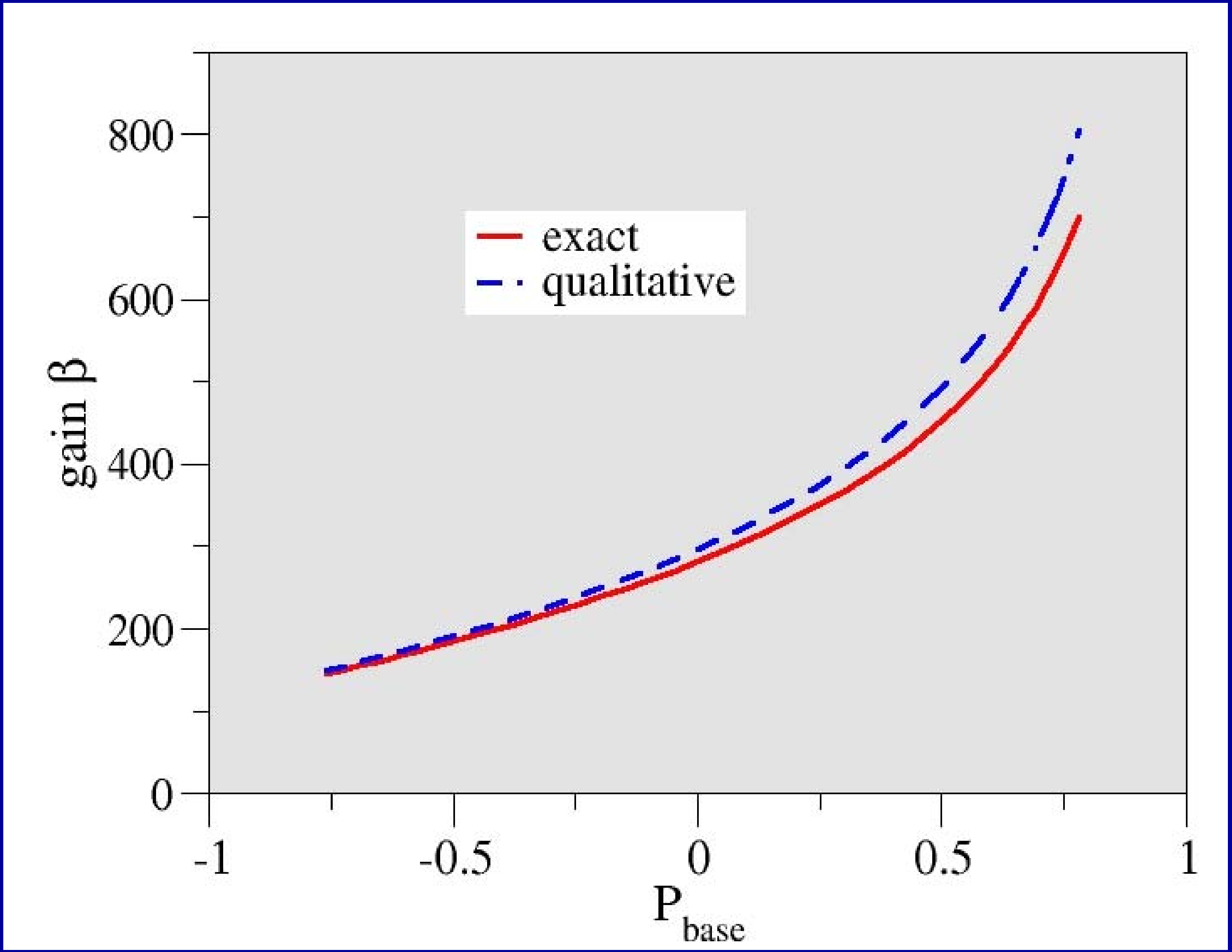
J. Fabian, I. Zutic, S. Das Sarma, Phys. Rev. B 66, 165301 (2002)

(giant) magnetoamplification



magnetoamplification: $\delta\beta = \frac{\delta J_c}{J_b} \sim \frac{\delta J_e}{J_b} \sim \delta P_e \cdot P_b$

Numerical calculation



Bipolar spintronic devices

- Spin-polarized p-n junction diode, spin capacitance

  I. Zutic, J. Fabian and S. Das Sarma, Phys. Rev. B 64, 121201 (2001)
- Spin-polarized solar cell

  I. Zutic, J. Fabian and S. Das Sarma, Appl. Phys. Lett. 79, 1558 (2001)
- Magnetic bipolar diode (MBD), GMR, spinvoltaic effect, spin injection, spin extraction

  I. Zutic, J. Fabian and S. Das Sarma, Phys. Rev. Lett. 88, 066603 (2002)
- General theory of magnetic bipolar devices

  J. Fabian. I. Zutic, and S. Das Sarma, Phys. Rev. B 66, 165301 (2002)
- Magnetic bipolar transistor (MBT)

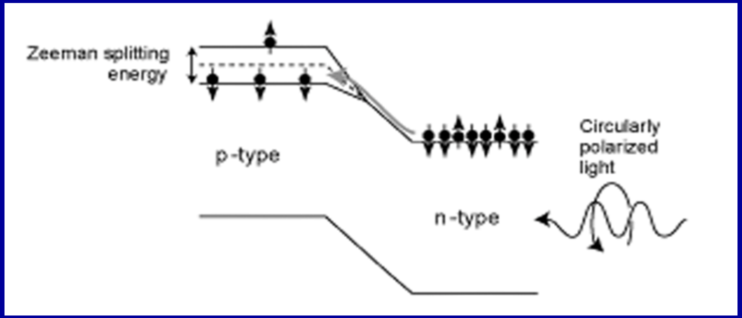
  J. Fabian, I. Zutic, and S. Das Sarma, cond-mat/0211639; Appl. Phys. Lett. 84, 85 (2004)

  J. Fabian and I. Zutic, Phys. Rev. B 69, 115314 (2004); Appl. Phys. Lett. (2005)
- Review

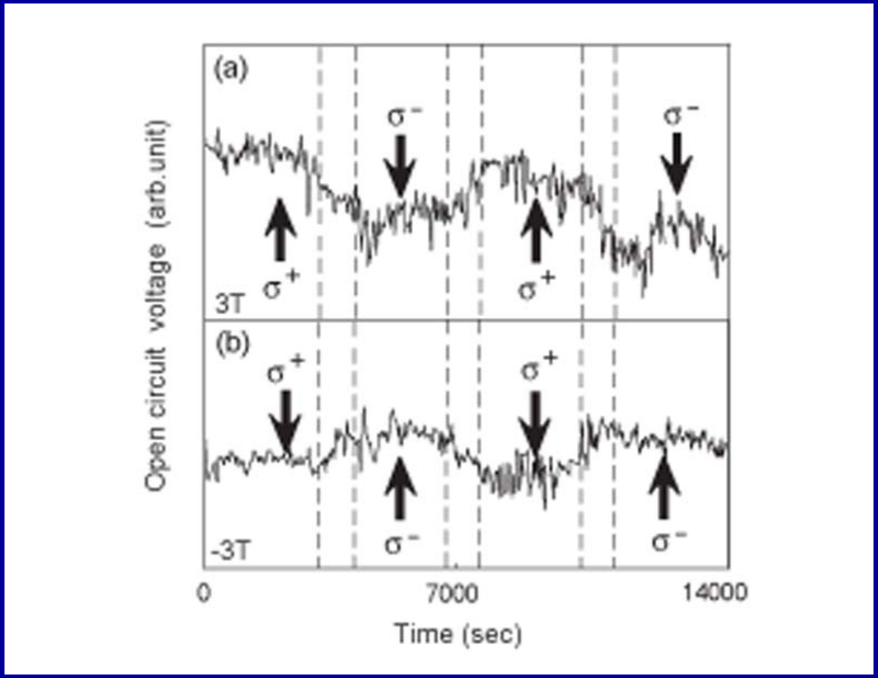
  I. Zutic, J. Fabian and S. Das Sarma, Rev. Mod. Phys. 76, 323 (2004)

experimental observation of spin-voltaic effect in p-n junctions

$In_{0.3}Ga_{0.7}As$
$g \approx -1.9$



$Al_{0.12}Ga_{0.88}As$
$g \approx 0$

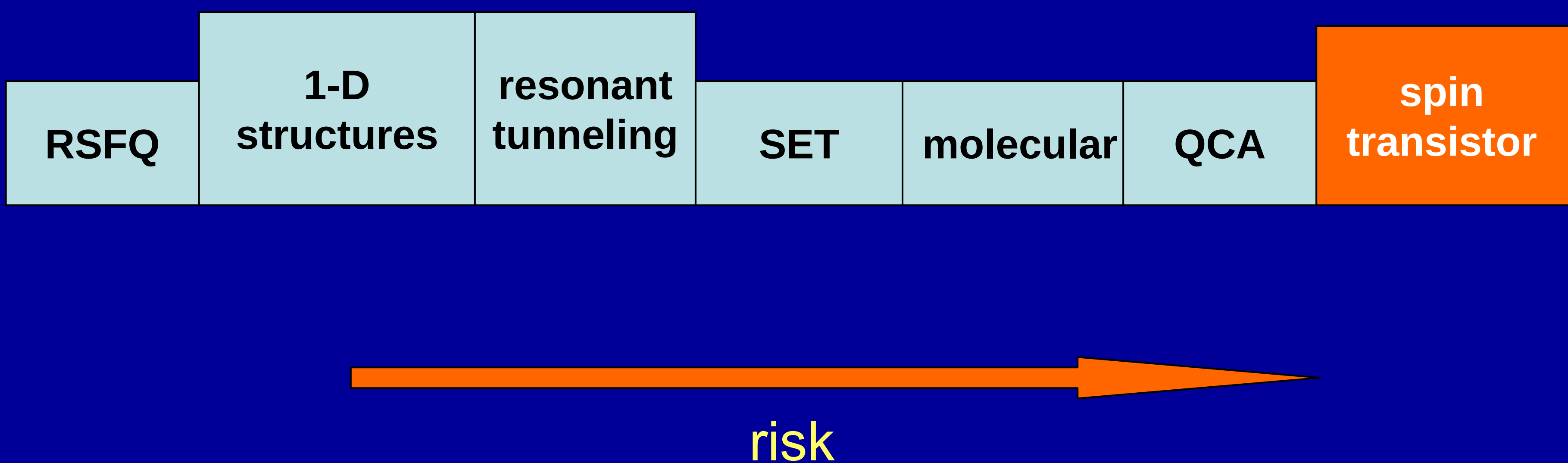


H. Munekata, in Concepts in Spin Electronics, Ed. S. Maekawa, (January 2006)

International Technology Roadmap for Semiconductors 2004:

Emerging Research Devices

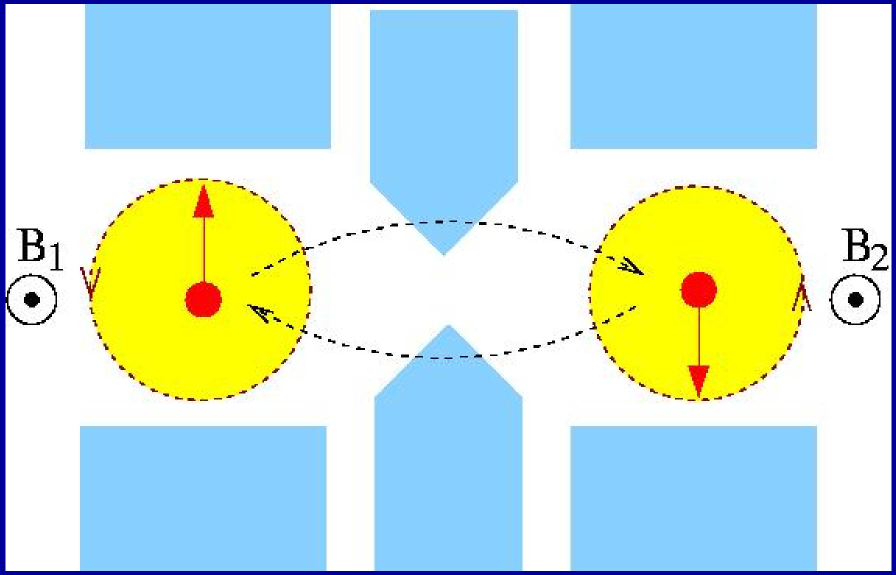
logic devices



:nanospintronics:

spin-based quantum information processing

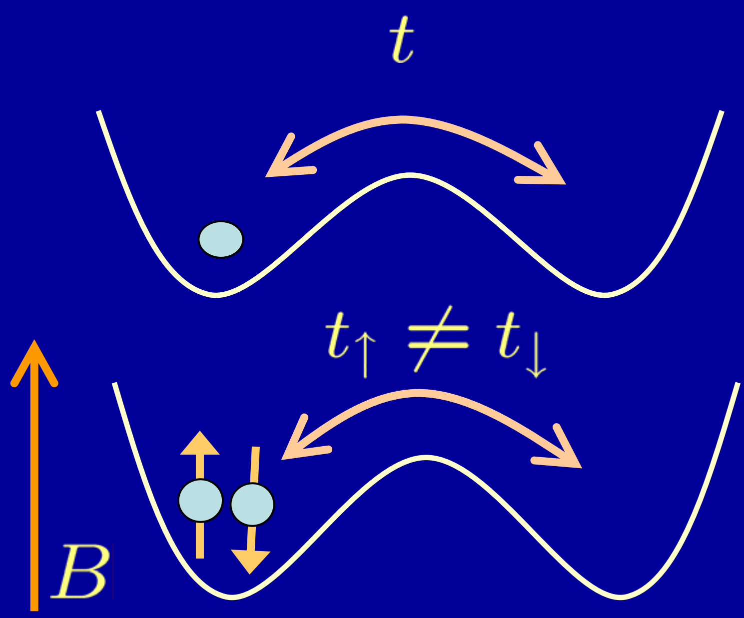
D. Loss and D. P. DiVincenzo, PRA 57, 120 (1998)



$$H(t) = \sum_{<i,j>} J_{ij}(t)\mathbf{S}_i \cdot \mathbf{S}_j + g^* \mu_B \sum_i \mathbf{S}_i \cdot \mathbf{B}_i(t)$$

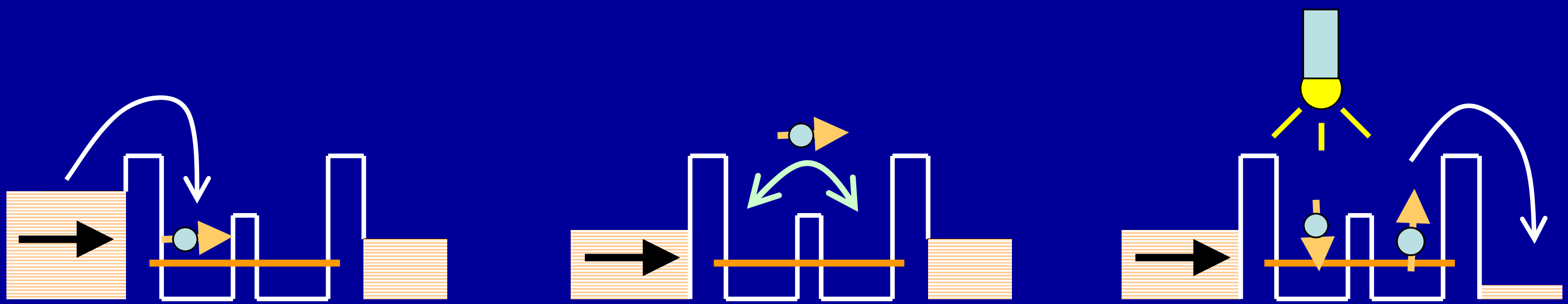
spin-to-charge conversion

spin-dependent tunneling



$t \sim 0.1$ meV, $T \sim 1$ ps, $T_1 > 1$ns

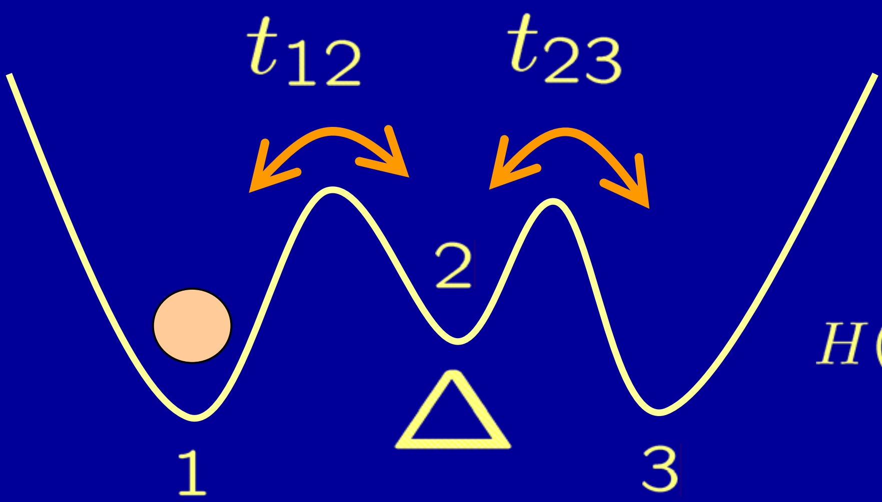
$$|t_\uparrow - t_\downarrow| \sim \alpha_{SO}^2 \times (\mu_B B/\epsilon_0) \times t$$
$$\sim 10^{-2} - 10^{-3} \times t$$



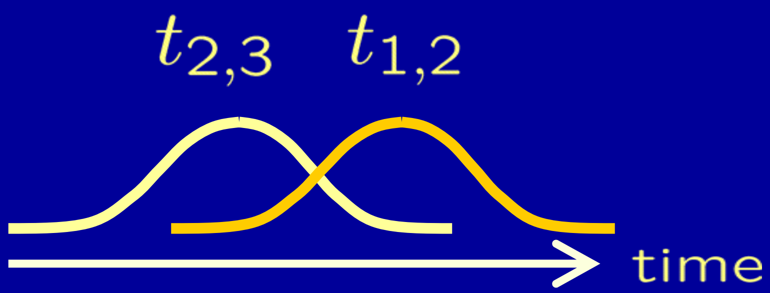
time $= 0$ | $100 - 1000$ oscillations | time $= \hbar/|t_\uparrow - t_\downarrow|$

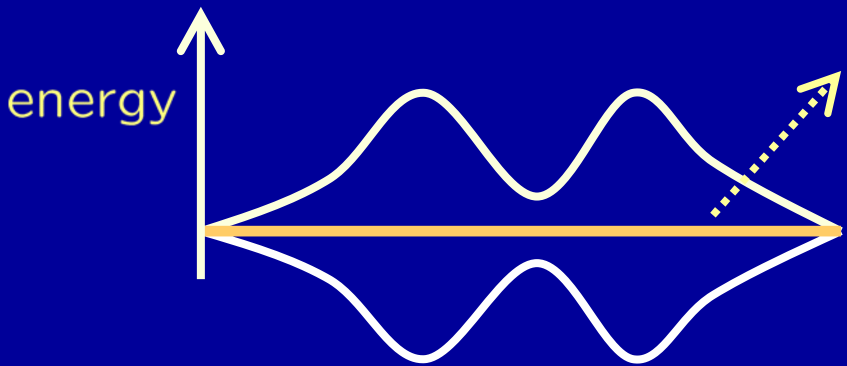
P. Stano and J. Fabian, Phys. Rev. B 72, 155410 (2005)

STIRAP: stimulated Raman adiabatic passage



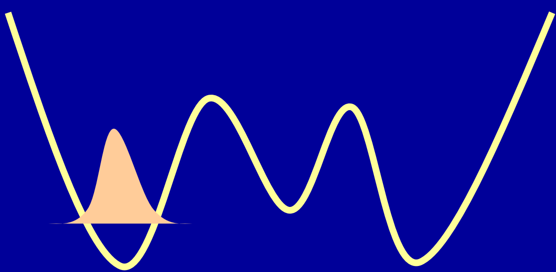
$$H(t) = \sum_i \epsilon_i n_i + \sum_{\langle i,j\rangle} t_{ij}(t)\ a_i^+ a_j$$



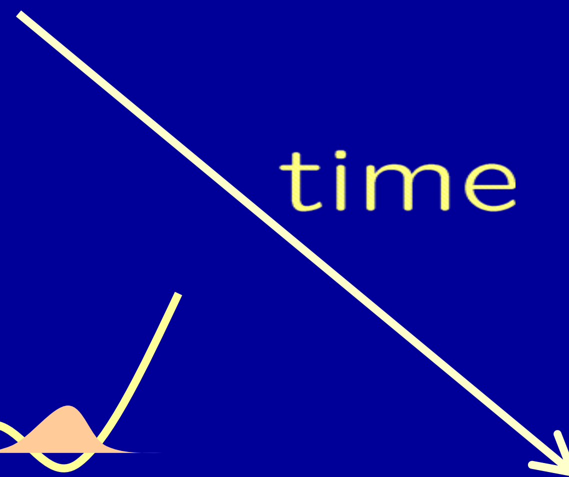


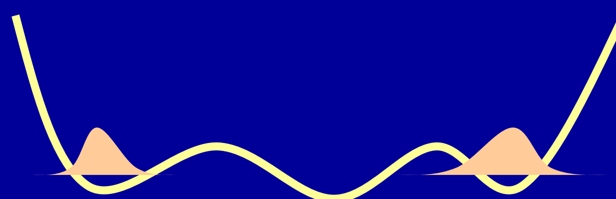
$$\Psi_{\text{trapped}}(t) \sim t_{2,3}|1\rangle - t_{1,2}|3\rangle$$

transfer through middle dot
without
transfer through middle dot

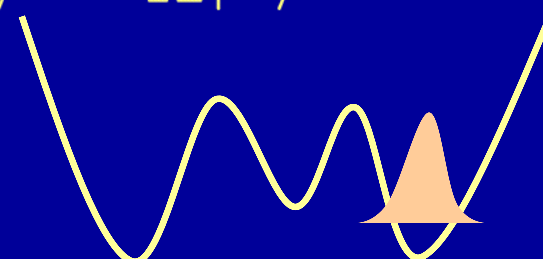


$$\Psi(0) = |1\rangle = \Psi_{\mathrm{trapped}}(0)$$





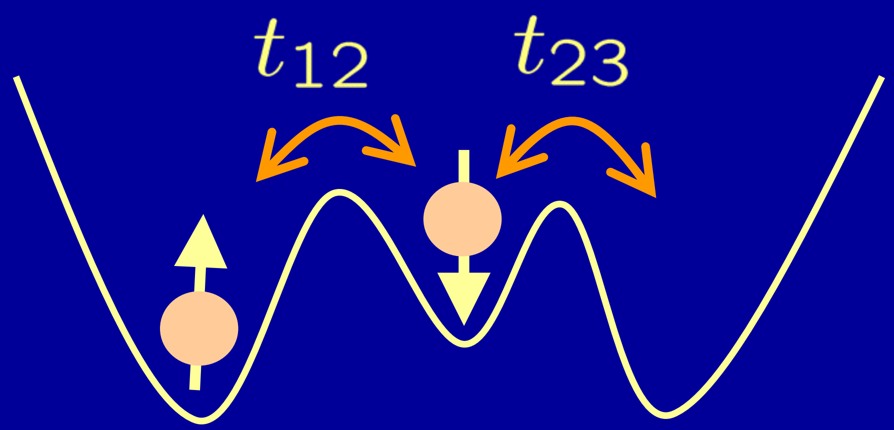
$$\Psi(t) = \Psi_{\mathrm{trapped}}(t) \sim t_{23}|1\rangle - t_{12}|3\rangle$$



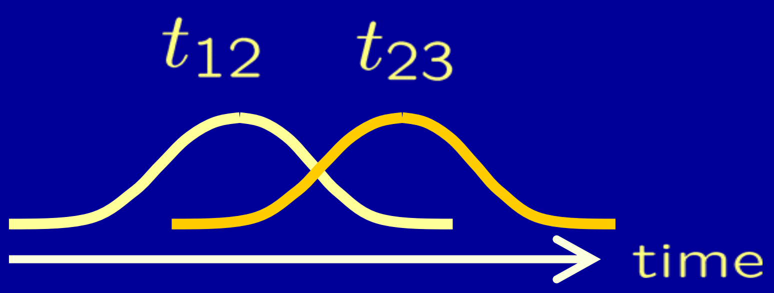
$$\Psi(\infty) = \Psi_{\mathrm{trapped}}(\infty) = |3\rangle$$

EDAP

entanglement distillation by adiabatic passage

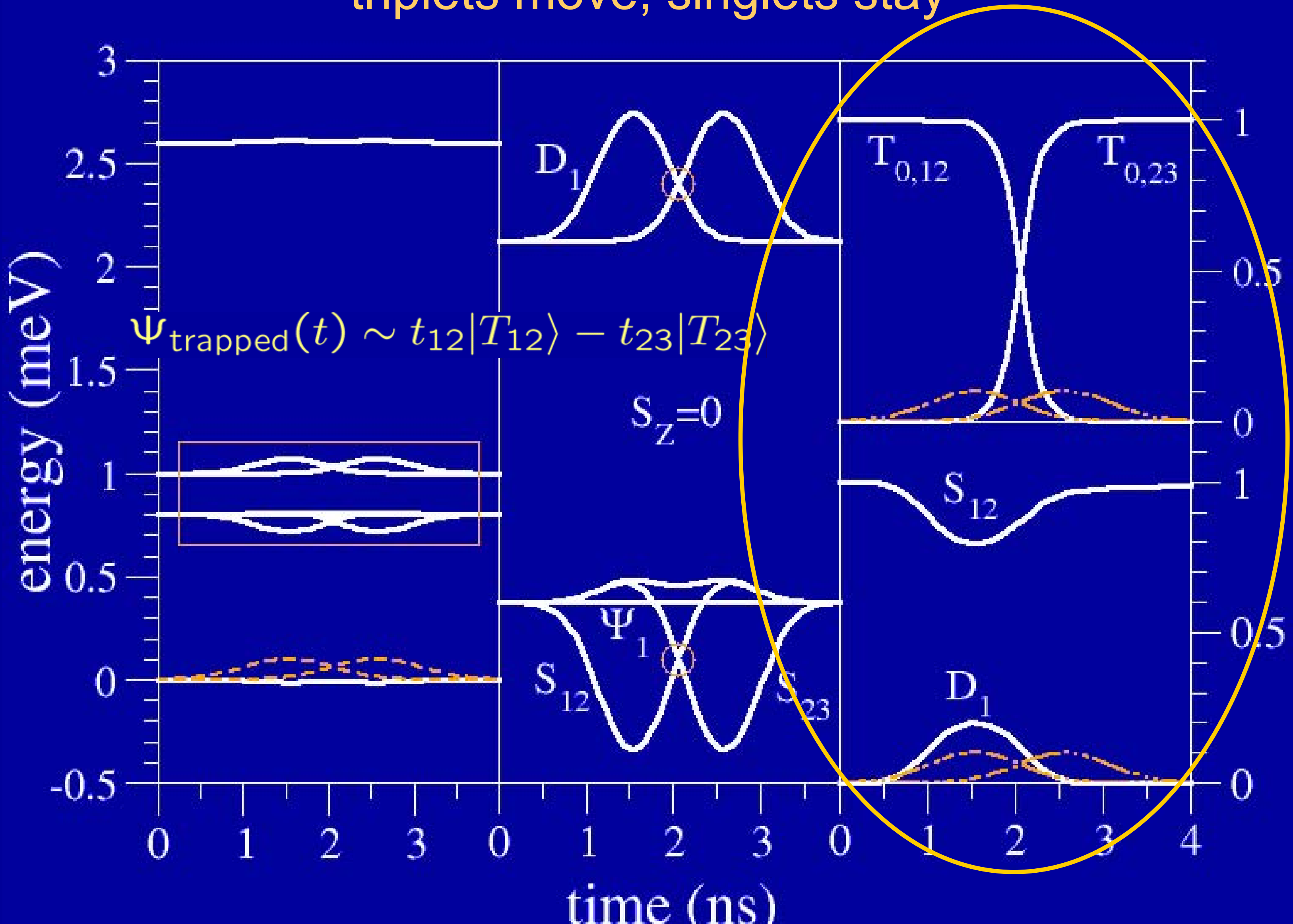


$$H(t) = \sum_i \epsilon_i n_i + \sum_{\langle i,j \rangle} t_{ij}(t)\; a_i^+ a_j + U \sum_i n_{i\uparrow} n_{i\downarrow}$$



entanglement-selective transfer:

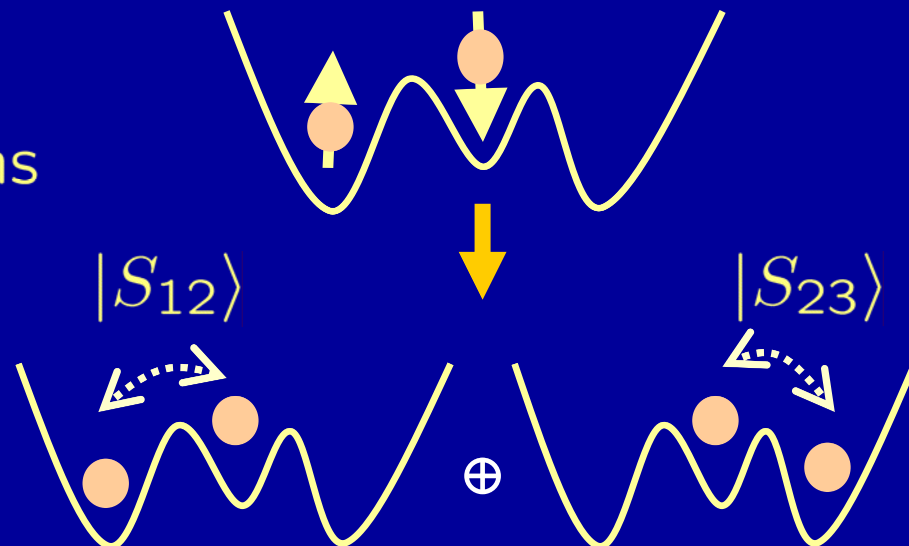
triplets move, singlets stay



J. Fabian and U. Hohenester, Phys. Rev. B (in press)

EDAP scheme:

entanglement-to-charge conversion



1. start with uncorrelated spins
$\Psi(0) = a|S_{12}\rangle + b|T_{12}\rangle.$

2. perform EDAP
$\Psi(\infty) = ae^{i\phi_S}|S_{12}\rangle + be^{i\phi_T}|T_{23}\rangle.$

3. perform *charge* measurement on one dot

4. the wave function collapses to either singlet ot triplet
$\Psi(\infty) \rightarrow \rho(\infty) = |a|^2|S_{12}\rangle\langle S_{12}| + |b|^2|T_{23}\rangle\langle T_{23}|$

J. Fabian and U. Hohenester, Phys. Rev. B (in press)

Conclusions

- new fundamental effects of spin-charge coupling
- bipolar spintronics devices viable niche for magnetic semiconductors
- spin quantum information processing in coupled dots: single and few spin manipulation, relaxation and decoherence, spin entanglement control

- new designs for GaMnAs-based devices
- silicon spintronics
- spin and charge coherence in mesoscopic transport
- multispin entanglement control

Collaborators: I. Zutic (SUNY Buffalo), S. Das Sarma (UMD), J. Tse (UMD), P. Stano (U.R), U. Hohenester (U. Graz)