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High Frequency Behavior of the Datta-Das and Resonant Spin Lifetime Transistors

Hender López, Xavier Oriols, Jordi Suñé and Xavier Cartoixà

Departament d'Enginyeria Electrònica
Universitat Autònoma de Barcelona, Spain

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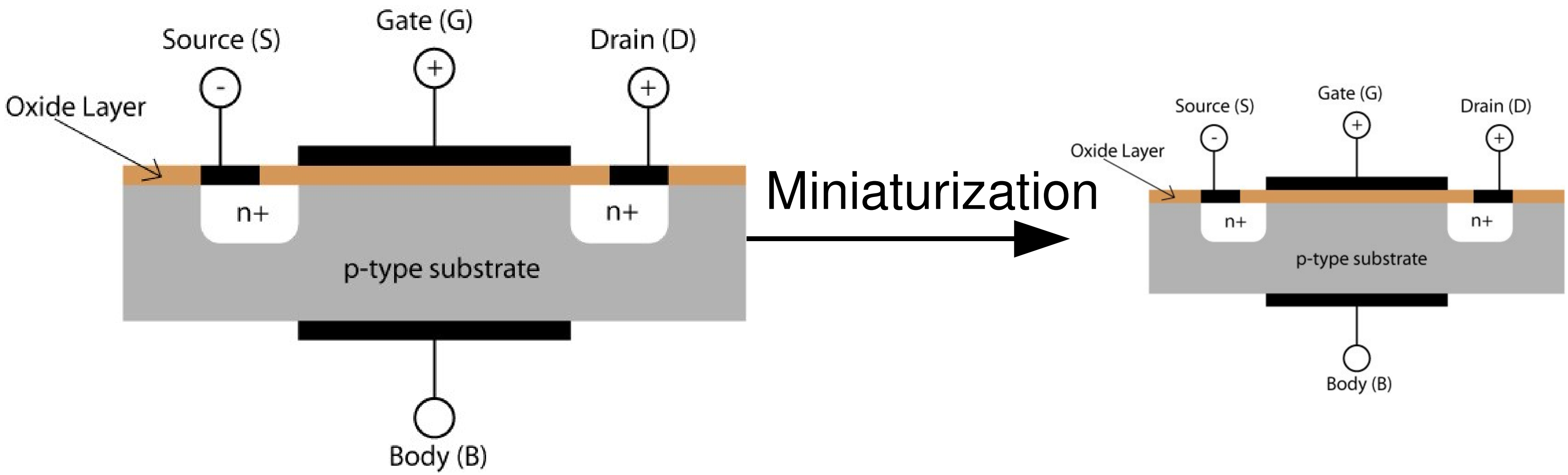
Introduction



Alternative: Semiconductor spintronics devices

Theoretical studies will help design and optimize devices

Device simulations

1)Datta-Das Spin Transistor

2)Resonant Spin Lifetime Transistor

Methodology

1) Semiconductor electronic transport → Monte Carlo method

[see Jacoboni and Reggiani, *Rev. Mod. Phys.* **55**, 645 (1983)]

2)To include spin dynamics: **S***(t)*

$$\frac{d\mathbf{S}(t)}{dt} = \mathbf{\Omega}_{eff} \times \mathbf{S}(t)$$

Simulation of Spin-FETs

[see Saikin *et al.*, *IEE Proc. Circuits Devices Syst.* **152**, 366 (2005)]

3)The injection process

Efficient Spin Injection → Ferromagnetic |TB| Semiconductor

Spin dependent contact resistance

Nonunity Probabilities → Injection/Extraction

DC and AC situations

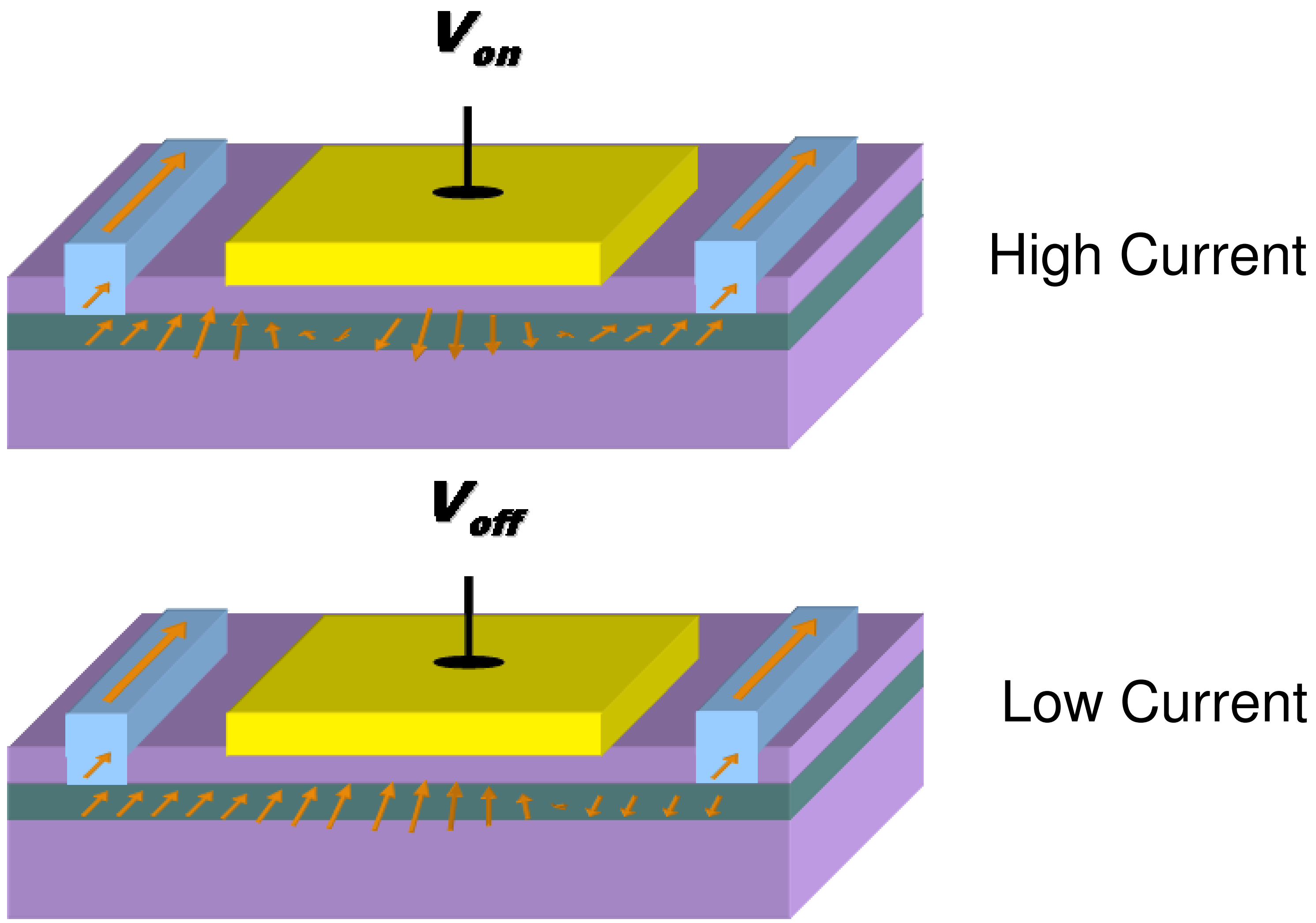
[López *et al.*, *JAP* **104**, 073702 (2008)]

Device simulations

Datta-Das Spin Transistor

Datta-Das Spin Transistor

First propose by Datta and Das [*APL*, **56** 665 (1990)]



Datta-Das Spin Transistor

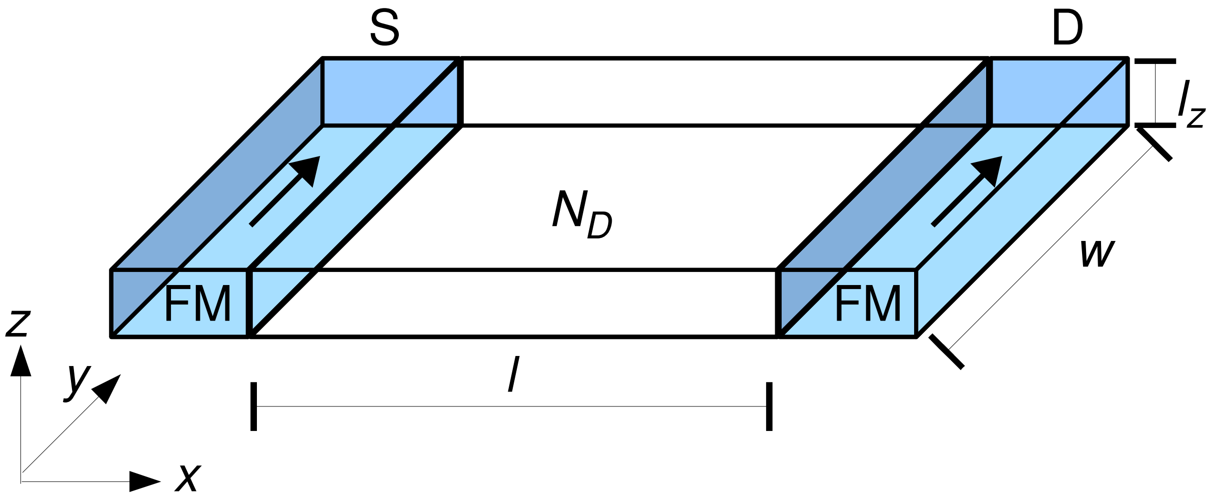
The Rashba spin-orbit interaction controls the spin rotation and acts as a k-dependent effective magnetic field

$$H_{\text{spin}}(\vec{k}, t) = \alpha(\sigma_x k_y + \sigma_y k_x)$$
$$= \hbar \mathbf{\Omega}_{eff}(\vec{k}, t) \cdot \sigma$$

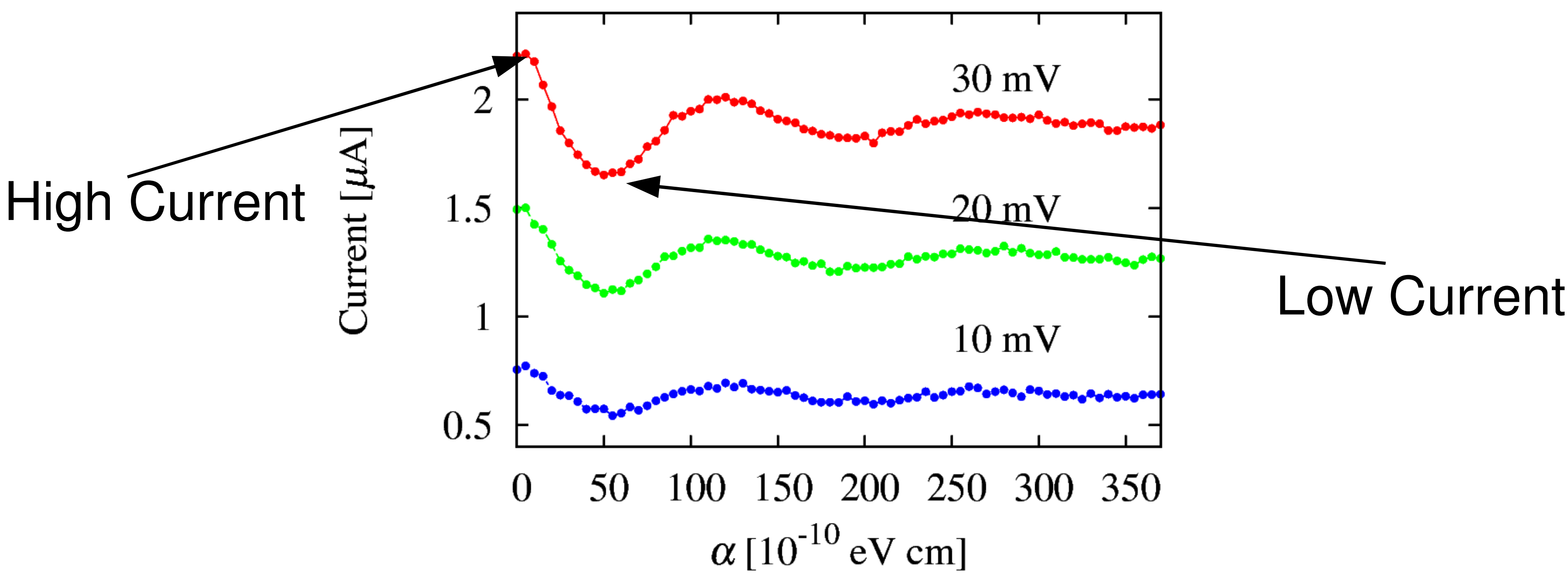
Rashba parameter is structure dependent and can be controllable by an external gate bias.

But to operate:
Transport must be ballistic

Datta-Das Spin Transistor



GaAs @ T=300 K: l = 20 nm, w = 50 nm, lz = 10 nm

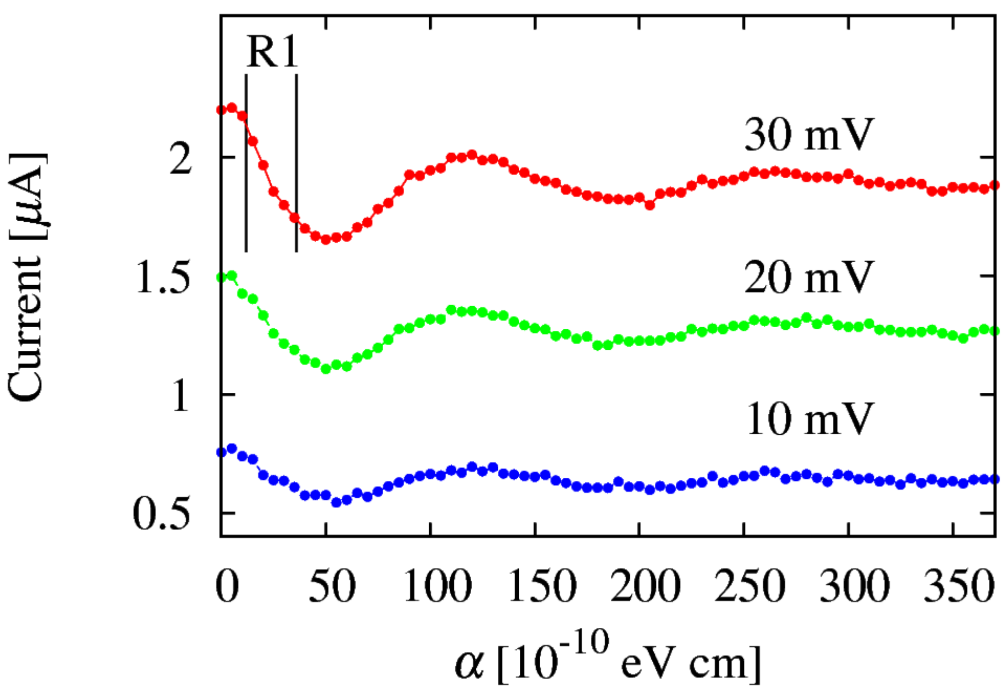


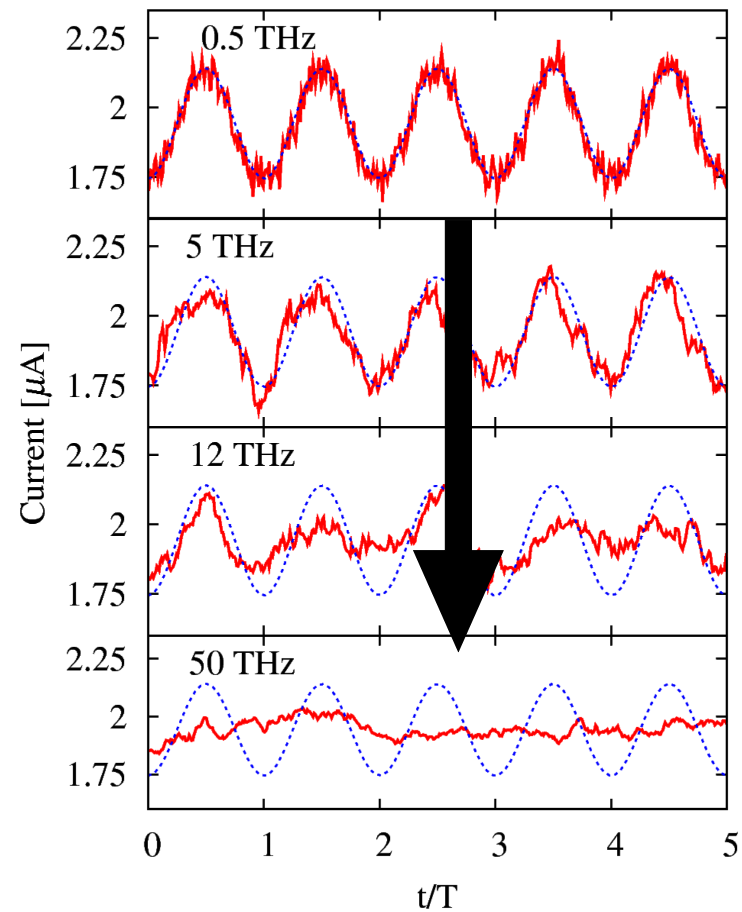
Datta-Das Spin Transistor

AC simulations

$$H_{\text{spin}}(\vec{k},t) = \left[\alpha_{\text{DC}} + \alpha_{\text{AC}}\cos\omega t\right]\left(\sigma_x k_y + \sigma_y k_x\right)$$

Time-dependent Rashba coefficient

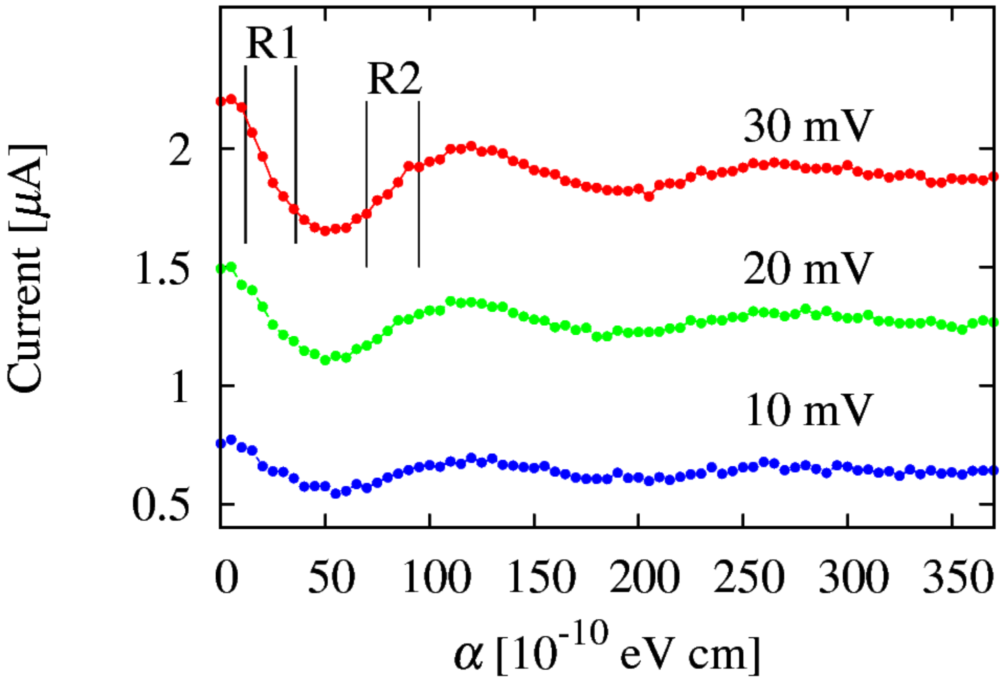




Datta-Das Spin Transistor

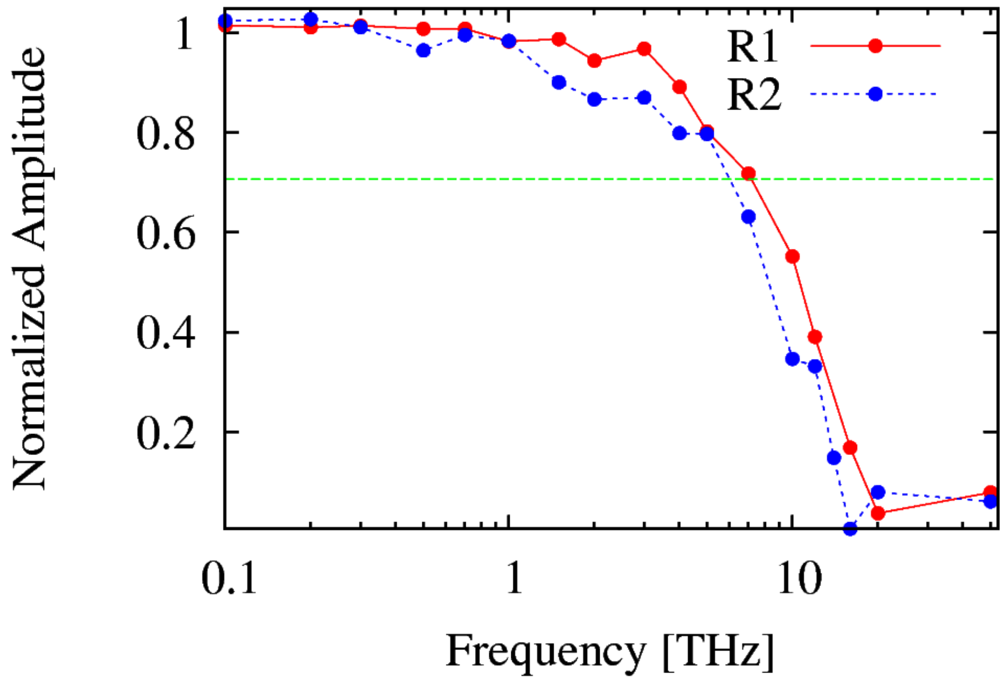
The ultimate limiting factor to the cutoff frequency

Transit time or Larmor frequency?

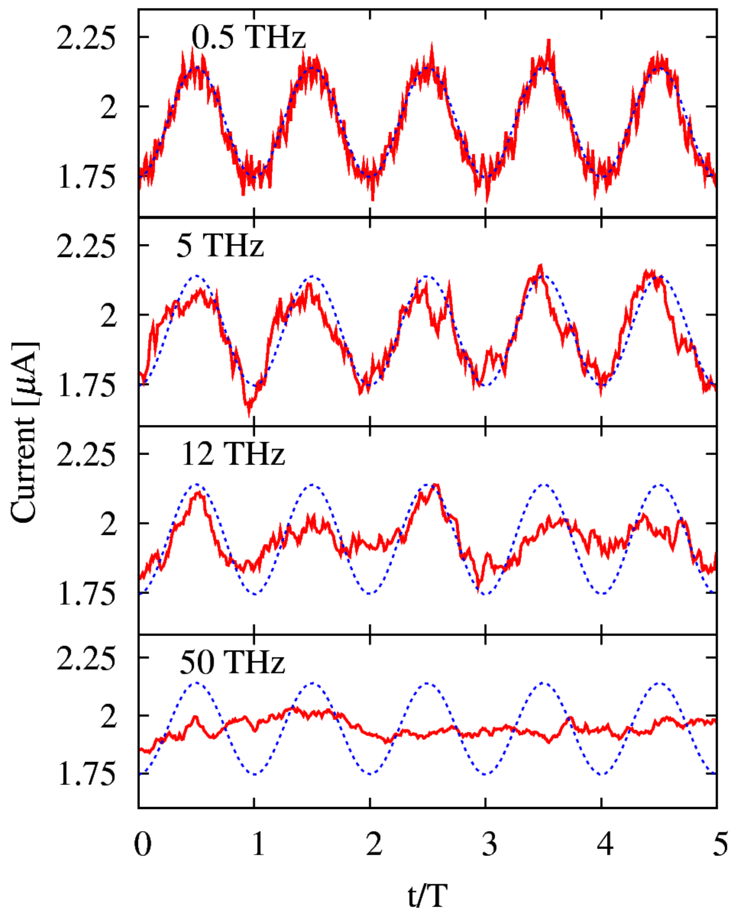


	R1	R2
Ω_{eff}(THz)	11.7	39.0
Transit Time (fs)	57	67

Datta-Das Spin Transistor

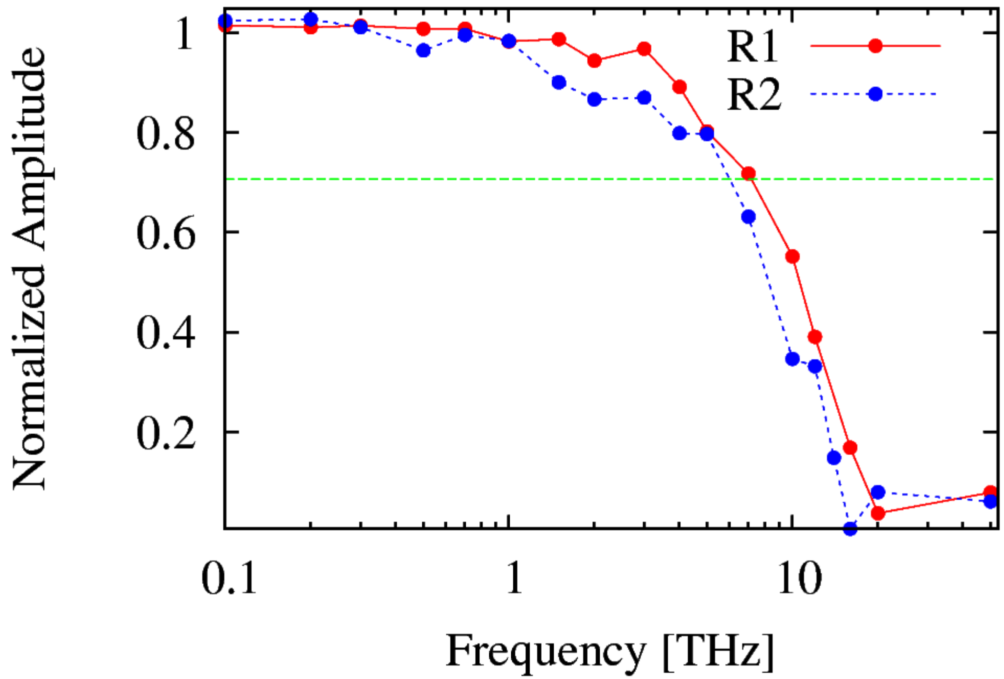


Fourier Transform



Datta-Das Spin Transistor

Cutoff frequency



Transit time or Larmor frequency?

Transit time

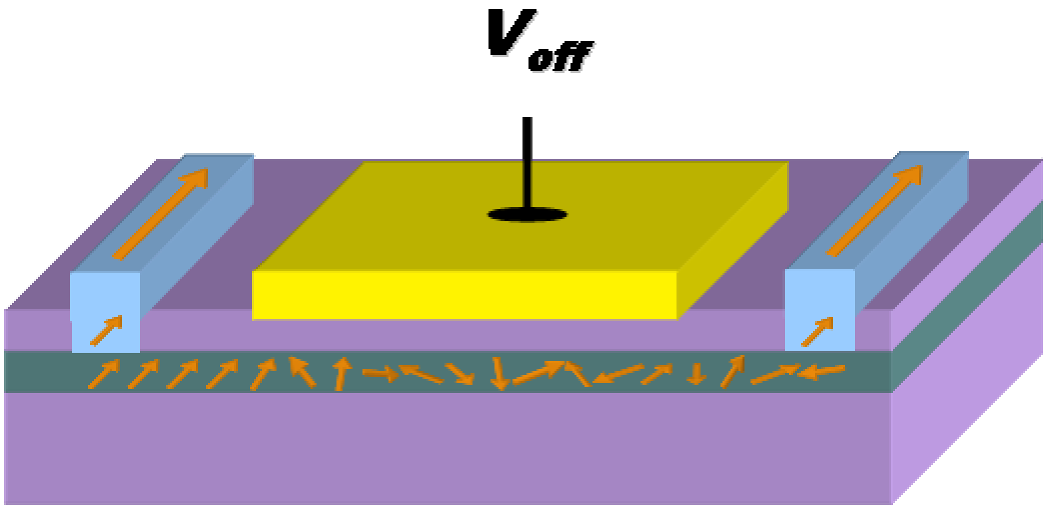
	R1	R2	Ratio
Ω_{eff}(THz)	11.7	39.0	0.30
Transit Time (fs)	57	67	1.17
ω_c (THz)	7.2	6.1	1.18

[López *et al.*, *APL* **93**, 193502 (2008)]

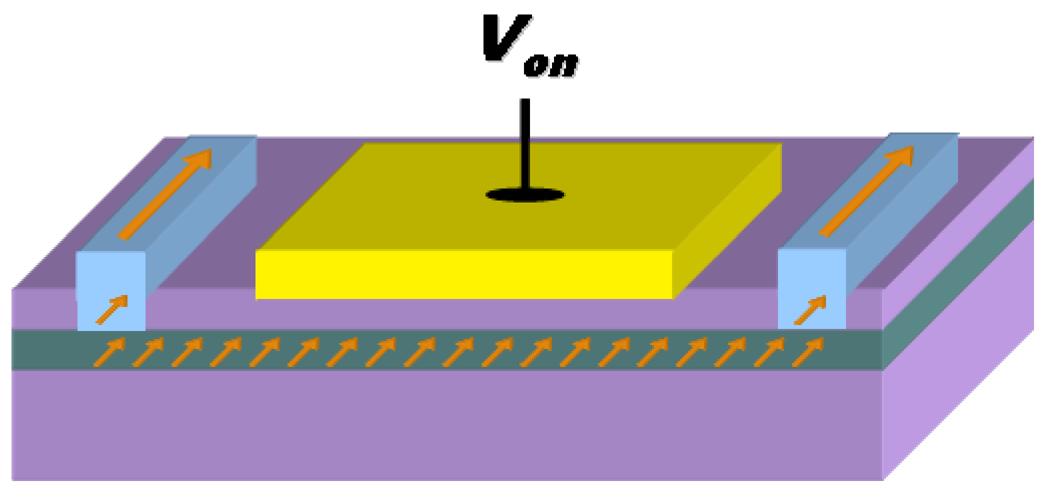
Device simulations

Resonant Spin Lifetime Transistor

Resonant Spin Lifetime Transistor



Modulating the relative strength
between the Rashba (BIA) and Dresselhaus (SIA) effects.



Cartoixa *et al.*, *APL* **83**, 1462 (2003)
Schliemann *et al.*, *PRL* **90**, 146801(2003)

Resonant Spin Lifetime Transistor

Now effective Larmor frequency has two contributions

$$\mathbf{\Omega}_{eff}(\vec{k}) = \mathbf{\Omega}_{BIA}(\vec{k}) + \mathbf{\Omega}_{SIA}(\vec{k})$$

Dresselhaus term

Rashba term

Resonant Spin Lifetime Transistor

Using the most general spin Hamiltonian up to 𝕆(k³) we have [Cubic Term Model (CTM)]:

$$\begin{aligned}\mathbf{\Omega}_{BIA}(\vec{k}) &= \frac{2}{\hbar}[\gamma_1(-k_x\hat{\imath}+k_y\hat{\jmath}) \\ &+\gamma_{31}(k_x^3\hat{\imath}-k_y^3\hat{\jmath}) \\ &+\gamma_{32}(k_xk_y^2\hat{\imath}-k_x^2k_y\hat{\jmath})]\end{aligned}$$

$$\begin{aligned}\mathbf{\Omega}_{SIA}(\vec{k}) &= \frac{2}{\hbar}[\alpha_1(k_y\hat{\imath}-k_x\hat{\jmath}) \\ &+\alpha_{31}(-k_y^3\hat{\imath}+k_x^3\hat{\jmath}) \\ &+\alpha_{32}(-k_x^2k_y\hat{\imath}+k_xk_y^2\hat{\jmath})]\end{aligned}$$

where the constants α_i's and γ_i's parametrize the different contributions to the spin splitting

[Cartoixa *et al.*, *PRB* **73**, 205341 (2006)]

Resonant Spin Lifetime Transistor

When:

$$\gamma_{32} = \gamma_{31} = \alpha_{31} = \alpha_{32} = 0$$

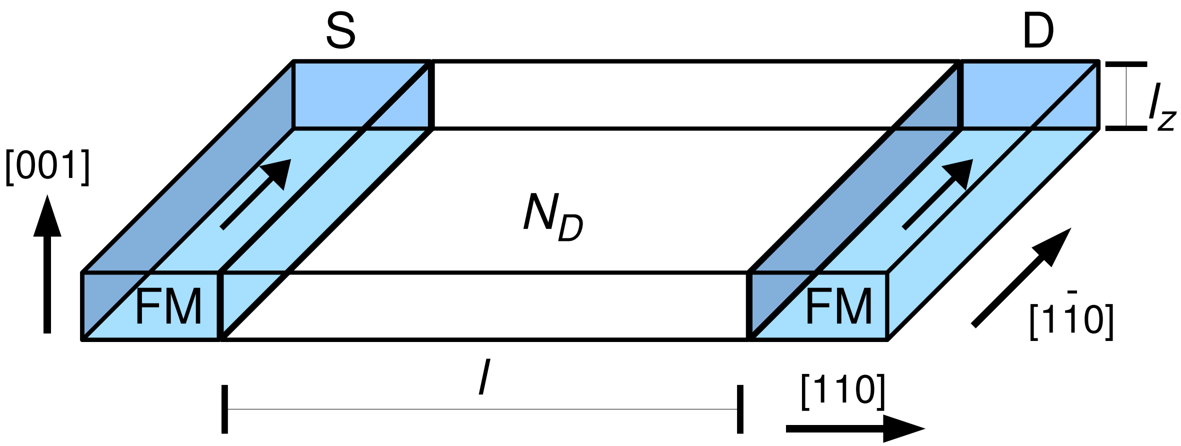
we obtain the Linear Term Model (LTM)

Substituting:

$$\alpha_1 = \alpha; \alpha_{31} = \alpha_{32} = 0; \gamma_1 = \gamma_D \left\langle k_z^2 \right\rangle ; \gamma_{31} = 0; \gamma_{32} = \gamma_D$$

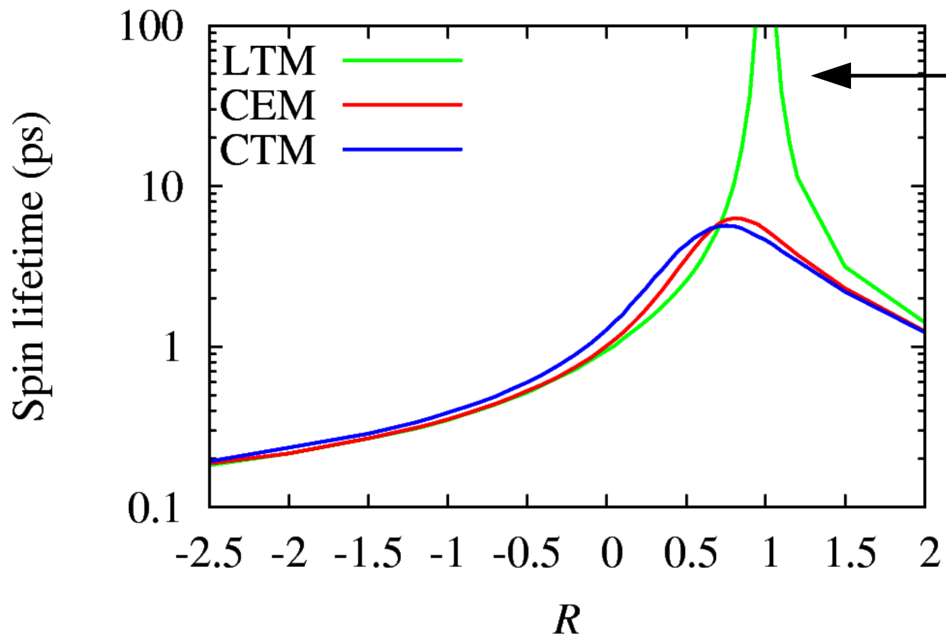
we obtain the Common Expression Model (CEM)

Resonant Spin Lifetime Transistor



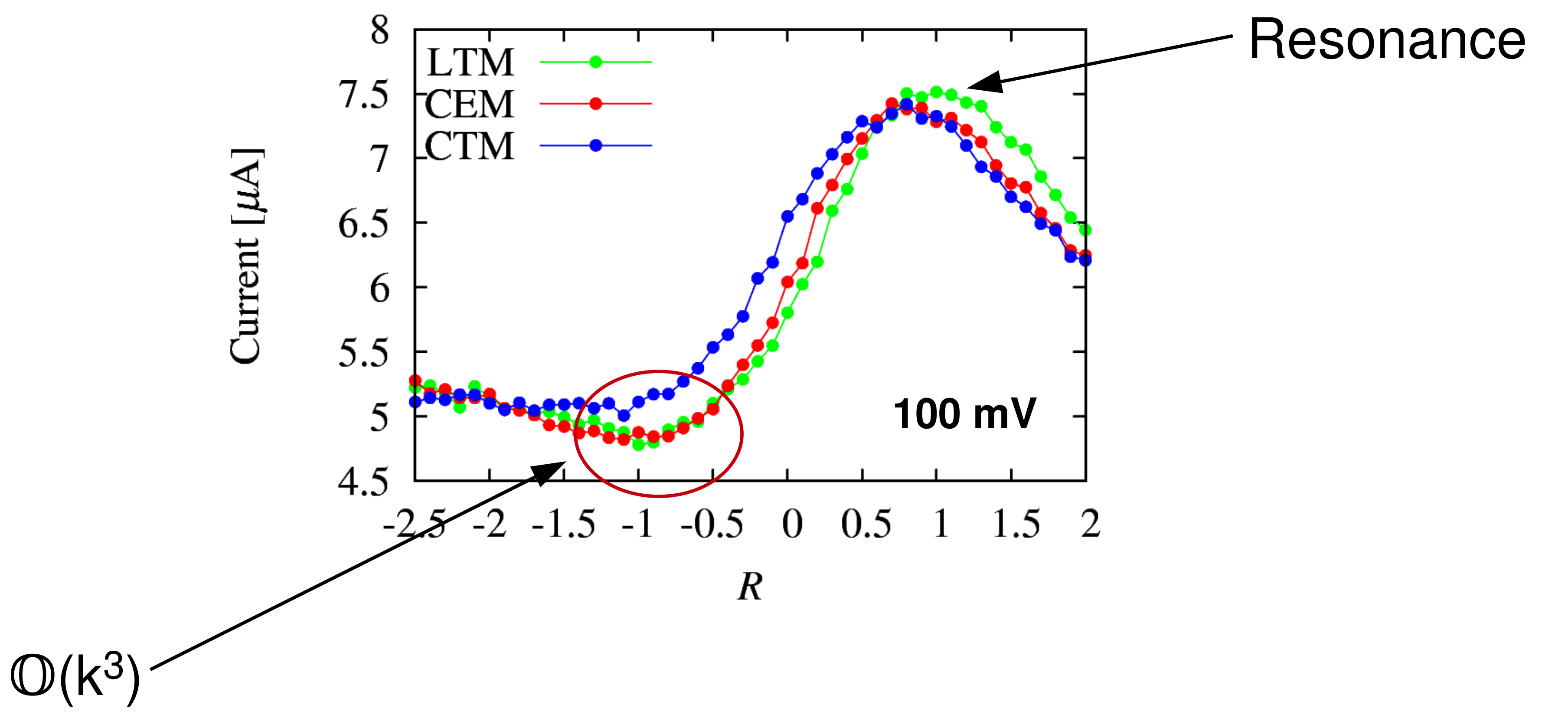
GaAs @ T=300 K: l = 150 nm,
lz = 2.3 nm

$$R = \frac{\alpha_1}{\gamma_1}$$



Resonance only observed for the LTM

Resonant Spin Lifetime Transistor



Resonant Spin Lifetime Transistor

The ultimate limiting factor to the cutoff frequency

Transit time or Larmor frequency?

Now we change the length of the channel

Length (nm)	75	150	Ratio
Ω_{eff}(GHz)	336	340	0.99
Transit Time (ps)	300	734	2.45
ω_c (GHz)	334	205	1.63

Conclusions

•Static and dynamic behavior of the DDST and RSLT were studied using the device Monte Carlo method which includes a spin-dependent injection model.

• We studied the current characteristics of the two spin transistors in DC situations.

• For both devices the **maximum operation frequency is controlled by the transit time, rather than the Larmor frequency or the spin lifetime**.

•The effect of $\mathbb{O}(k^3)$ terms in the Rashba Hamiltonian has been analyzed.