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

Funding: European Commission's Marie Curie International Reintegration Grant and the Spanish Ministry of Science and Technology
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

2) To include spin dynamics: \( S(t) \)
   \[ \frac{dS(t)}{dt} = \Omega_{eff} \times S(t) \]

Simulation of Spin-FETs

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)]

$V_{on}$

High Current

$V_{off}$

Low Current
Datta-Das Spin Transistor

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

\[ H_{\text{spin}}(\vec{k}, t) = \alpha (\sigma_x k_y + \sigma_y k_x) = \hbar \Omega_{\text{eff}}(\vec{k}, t) \cdot \sigma \]

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: \( l = 20 \text{ nm} \), \( w = 50 \text{ nm} \), \( l_z = 10 \text{ nm} \)

Graph showing high current and low current at \( \alpha \) values of 10 mV, 20 mV, and 30 mV.
Datta-Das Spin Transistor

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

**AC simulations**

Time-dependent Rashba coefficient

![Graphs showing current as a function of alpha and time](image)
Datta-Das Spin Transistor

The ultimate limiting factor to the cutoff frequency

Transit time or Larmor frequency?

\[ \Omega_{eff} (\text{THz}) \]

<table>
<thead>
<tr>
<th>Transit Time (fs)</th>
<th>R1</th>
<th>R2</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.7</td>
<td>57</td>
<td>39.0</td>
</tr>
<tr>
<td>39.0</td>
<td>67</td>
<td></td>
</tr>
</tbody>
</table>
Datta-Das Spin Transistor

Fourier Transform

Normalized Amplitude

Frequency [THz]

Current [μA]

0.5 THz
5 THz
12 THz
50 THz
Datta-Das Spin Transistor

Transit time or Larmor frequency?

Transit time

<table>
<thead>
<tr>
<th></th>
<th>R1</th>
<th>R2</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Omega_{eff}$ (THz)</td>
<td>11.7</td>
<td>39.0</td>
<td>0.30</td>
</tr>
<tr>
<td>Transit Time (fs)</td>
<td>57</td>
<td>67</td>
<td>1.17</td>
</tr>
<tr>
<td>$\omega_c$ (THz)</td>
<td>7.2</td>
<td>6.1</td>
<td>1.18</td>
</tr>
</tbody>
</table>

[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)
Now effective Larmor frequency has two contributions

\[ \Omega_{\text{eff}}(\vec{k}) = \Omega_{\text{BIA}}(\vec{k}) + \Omega_{\text{SIA}}(\vec{k}) \]

- Dresselhaus term
- Rashba term
Resonant Spin Lifetime Transistor

Using the most general spin Hamiltonian up to $\mathcal{O}(k^3)$ we have

[Cubic Term Model (CTM)]:

$$\Omega_{BIA}(k) = \frac{2}{\hbar} \left[ \gamma_1 (-k_x \hat{i} + k_y \hat{j}) + \gamma_{31} (k_x^3 \hat{i} - k_y^3 \hat{j}) + \gamma_{32} (k_x k_y^2 \hat{i} - k_x^2 k_y \hat{j}) \right]$$

$$\Omega_{SIA}(k) = \frac{2}{\hbar} \left[ \alpha_1 (k_y \hat{i} - k_x \hat{j}) + \alpha_{31} (-k_y^3 \hat{i} + k_x^3 \hat{j}) + \alpha_{32} (-k_x^2 k_y \hat{i} + k_x k_y^2 \hat{j}) \right]$$

where the constants $\alpha_i$'s and $\gamma_i$'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:

\[ \alpha_1 = \alpha; \alpha_{31} = \alpha_{32} = 0; \gamma_1 = \gamma_D \langle k_z^2 \rangle; \gamma_{31} = 0; \gamma_{32} = \gamma_D \]

we obtain the Common Expression Model (CEM)
Resonant Spin Lifetime Transistor

GaAs @ T = 300 K: \( l = 150 \text{ nm, } l_z = 2.3 \text{ nm} \)

\[
R = \frac{\alpha_1}{\gamma_1}
\]

Resonance only observed for the LTM
Resonant Spin Lifetime Transistor

\[ \Theta(k^3) \]

\[ 100 \text{ mV} \]

Graph showing current vs. R with resonance indicated at 100 mV.
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

<table>
<thead>
<tr>
<th>Length (nm)</th>
<th>75</th>
<th>150</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Omega_{eff}$ (GHz)</td>
<td>336</td>
<td>340</td>
<td>0.99</td>
</tr>
<tr>
<td>Transit Time (ps)</td>
<td>300</td>
<td>734</td>
<td>2.45</td>
</tr>
<tr>
<td>$\omega_c$ (GHz)</td>
<td>334</td>
<td>205</td>
<td>1.63</td>
</tr>
</tbody>
</table>
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 $\mathcal{O}(k^3)$ terms in the Rashba Hamiltonian has been analyzed.