Spin Torque Oscillator from micromagnetic point of view

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What is a spin torque oscillator?

Why we are interested in ST oscillator?

Which are the modeling tools to describe them?

Out-of-plane precision (OPP)

In-plane precision (IPP)
Starting point…

The magnetization acts on the current $\rightarrow$ GMR / TMR phenomena

Action-reaction principle:

“Every action has an equal and opposite reaction.”

The polarized current acts on the magnetization $\rightarrow$ Spin torque phenomena
Starting point...

Basic picture ... ( J<0)

Exchange interaction between injected polarized $e^-$ ↑ and local magnetization causes the magnetization switching in the direction parallel to the spin of the injected $e^-$. 

Co

Cu

Co

Cu
Starting point…

Landau-Lifshitz-Gilbert equation + polarized current

\[
\begin{align*}
\frac{\partial \mathbf{M}}{\partial t} &= -\gamma_0 \left[ \mathbf{M} \times \mathbf{H}_{\text{eff}} \right] + \alpha \left( \mathbf{M} \times \frac{\partial \mathbf{M}}{\partial t} \right) + \left( \frac{\partial \mathbf{M}}{\partial t} \right)_{ST} \\
\mathbf{M}^2 &= 1
\end{align*}
\]
Perpendicular spin torque oscillator

Main goal → generate steady oscillations without applying field

Pt / (Co/Pt)/PEL /Cu/Py/Cu/Co/IrMn

Ellipse of 60x70 nm²

$I_{DC} = 0.15$ mA

$\Delta R = 0.19\, \Omega$

$MR = 0.3\%$

J. C. Slonczewski US5695864
K. J. Lee APL 86 (2005)
O. Redon US6,532,164 B2

Houssameddine et al. Nat. Mat. 6, 447 (2007)
Perpendicular spin torque oscillator

I = 0.15 mA

I = 1.1 mA

Intermediate resistance level (IRL)

There are two magnetoresistive states

Houssameddine et al. Nat. Mat. 6, 447 (2007)
Perpendicular spin torque oscillator

Static current-field diagram

Houssameddine et al. Nat. Mat. 6, 447 (2007)
Perpendicular spin torque oscillator

Static current-field diagram

Dynamic current-field diagram

Houssameddine et al. Nat. Mat. 6, 447 (2007)
Micromagnetic model

- Full 3D integration of

a) the Landau-Lifshitz-Gilbert (LLG) equation

\[
\frac{\partial \mathbf{M}}{\partial t} = -\gamma_0 [\mathbf{M} \times \mathbf{H}_{\text{eff}}] + \alpha \left( \mathbf{M} \times \frac{\partial \mathbf{M}}{\partial t} \right)
\]

\[
\mathbf{M}^2 = 1
\]

\[
\mathbf{H}_{\text{eff}} = -\frac{1}{\mu_0 M_s} \frac{\delta E}{\delta \mathbf{M}}
\]

\[
E = E_{\text{ex}} + E_{\text{anis}} + E_{\text{dem}} + E_{\text{app}}
\]

b) the magnetostatic equations

\[
\mathbf{H}_{\text{dem}}(\mathbf{r}) = -\int_V \nabla G(\mathbf{r} - \mathbf{r}') \rho_m(\mathbf{r}') dV' - \int_S \nabla G(\mathbf{r} - \mathbf{r}') \sigma_m(\mathbf{r}') dS'
\]
Micromagnetic model (2)

c) Addition term due to the spin torque transfer

\[
\begin{aligned}
\frac{\partial \mathbf{M}}{\partial t} &= -\gamma_0 \left[ \mathbf{M} \times \mathbf{H}_{\text{eff}} \right] + \alpha \left( \mathbf{M} \times \frac{\partial \mathbf{M}}{\partial t} \right) + \left( \frac{\partial \mathbf{M}}{\partial t} \right)_{ST} \\
\mathbf{M}^2 &= 1
\end{aligned}
\]

\[
\left( \frac{\partial \mathbf{M}}{\partial t} \right)_{ST} = -\gamma_0 a_J \left[ \mathbf{M} \times (\mathbf{M} \times \mathbf{m}_{\text{PL}}) \right]
\]

\[
\left( \frac{\partial \mathbf{M}}{\partial t} \right)_{ST} = c_0 \left[ \mathbf{m} \times \mathbf{M} \right]
\]

J. C. Slonczewski
JMMM. 159, L1 (1996)

« ballistic transport model »

A. Vedyeyev, D. Gusakova

« diffusive transport model »

ST-GLFFT

LLG_SA

Workshop on Advance Magnetic Materials / Cluj-Napoca (Romania) 16/09/2007
Micromagnetic model (3)

➢ Transport equation

\[
\frac{\partial j^m}{\partial z} + \frac{J_{sd}}{\eta} \mathbf{m} \times \mathbf{M} + \frac{\mathbf{m}}{\tau_{sf}} = 0
\]

electron current

\[j^e = j^\uparrow + j^\downarrow = \sigma_0 E_z - D_0 \partial_z n - D_0 \beta' (\mathbf{M} \cdot \partial_z \mathbf{m})\]

spin current

\[j^m \Rightarrow j^\uparrow - j^\downarrow = \sigma_0 E_z \beta \mathbf{M} - D_0 \partial_z \mathbf{m} - D_0 \beta' \mathbf{M} \partial_z n\]

\[
\left( \frac{\partial \mathbf{M}}{\partial t} \right)_{ST} = \frac{J_{sf}}{\mu_B} \mathbf{m} \times \mathbf{M}
\]
Micromagnetic model (4)

Transport equation

Graph showing magnetic behavior over time and distance with labels POL, FL, and AN, indicating different zones and magnetic orientations.
Perpendicular spin torque oscillator

Micromagnetic parameters

Fixed layer

- circular disk 60nm, thickness 3.5nm
- $M_s = 866 \text{ kA/m}$
- $K_u = 664.5 \text{ J/m}^3 \parallel Ox \quad (H_u=150 \text{ Oe})$
- $A_{ex} = 2 \cdot 10^{-11} \text{ J/m}$
- $\alpha = 0.01$
- Mesh size $2 \times 2 \times 3.5 \text{ nm}^3$

Fixed layer
Macrospin current-field diagram

POL-FL

IPS

OPP

OPS

applied magnetic field, Oe

current density, $10^7$ A/cm$^2$

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Macrospin current-field diagram

POL-FL-AN

current density, $10^7$ A/cm$^2$

applied magnetic field, Oe

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Macrospin current-field diagram

$H_{\text{app}} = 0$

current density, $10^7 \text{ A/cm}^2$
OPP frequency

No applied field

![Graph showing OPP frequency vs. applied field strength for different sample types and conditions.](image-url)
OPP frequency

No applied field

→ $\mu$mag simulation

→ experimental data

![Graph showing OPP frequency vs. J$_{app}$ (A/m$^2$) for macro and micro samples, and experimental data points.](image1)

![Graph showing OPP frequency vs. I$_{app}$ (mA) with H$_{bias}$=-371Oe.](image2)
OPP frequency

No applied field
OPP frequency

No applied field

![Graph showing OPP frequency for macro and micro samples with different applied fields. The graph includes markers for POL-FL and POL-FL-AN.](image-url)
OPP frequency

No applied field

![Graph showing OPP frequency with frequency on the y-axis and applied field on the x-axis. The graph includes data points for different samples labeled macro, micro, POL-FL, and POL-FL-AN.](image)
Perpendicular spin torque oscillator

Static current-field diagram

Dynamic current-field diagram

Houssameddine et al. accepted Nat. Mat.
IPP frequency

→ experimental data

→ μmag simulation

\[
I_{DC} (mA) \quad I_{mag} = \frac{0.8 \times 10^{10} A/m^2}{\mu_0 H_{app} (mT)}
\]

\[
\begin{align*}
J_{app} &= 0.8 \times 10^{10} A/m^2 \\
\mu_0 H_{app} (mT) &\quad \text{Frequency (Hz)}
\end{align*}
\]
Temperature effects

No applied field

→ μmag simulation

![Graph showing frequency vs. applied field strength with labels for macro, micro, POL-FL, and POL-FL-AN.]
Conclusion

Solving self-consistently the LLG equation and the spin dependent transport equation:

a) accurate investigation of structures with 2, 3 or more coupled magnetic layers

b) qualitative good agreement with the experimental data

c) "A toy" dedicated to the ST oscillator optimization for future device integration