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Comparison of Spin Current in Spin Circuit With Nano-Magnetic Nodes and Two Different Nano-Channels

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Abstract

Electronics of spin or spintronics is a newfangled field which its purpose is to study the role of electron's spin in solid-state devices. spintronic devices require spin current. Spin current is a difference between spin-up and spin-down electric currents. In this paper, we intend to calculate and compare spin currents of two spin circuits' branches by considering two different nano-channels (copper and gold). Also we investigate simultaneously effects of nano-channels length and cross section area variations on them. Our findings show that spin current in series branch increase by simultaneously length of nano-channel reduction and rising of cross section area. For spin flip branches, we can reduce dissipation by simultaneously decrease of length and cross section area nano-channel. We choose copper metal as nano-channel because of longer spin diffusion length, less spin current dissipation and equality of its lattice constant with those of permalloy.

Keywords: Circuit, Spin, Current, Conduction, Nano, Channel.

1. Introduction

Electronics of spin or spintronics is a newfangled field which its purpose is to study the role of electron's spin in solid-state devices. Spintronics emerged from discoveries in the 1980s concerning spin-dependent electron transport phenomena. Just as conventional electronic devices require charge current, spintronic devices require spin current (Žutić, et al., 2004). Spin current is a difference between spin-up and spin-down electric currents. A spin polarization of the current is expected from the different conductivities resulting from the different densities of states for spin-up and spin-down electrons in the ferromagnetic materials. Comfortable way to create spin current is passing electron current form ferromagnetic materials. Spin injectors are materials which create spin-polarized electron injection. There have been many choices for spin injectors but the most obvious choice are ferromagnetic materials due to their high Curie temperatures, low coercivities and fast switching times. In this paper, we intend to calculate and compare spin currents of two spin circuits' branches by considering two different nano-channels (copper and gold). For achieve this aim, we start with description of laws governing on spin circuits (section 2). Sections 3 and 4 are devoted to calculation of spin current in Π and T-shaped spin circuit, respectively. Also we investigate simultaneously effects of nano-channels length and cross section area variations on spin current in section 4. Finally, we present conclusion and discussion in section 5.

2. Laws Governing on Spin Circuits

Spin circuit with nano-magnetic nodes and non-magnetic channel is one of the circuits group in which flows spin current in addition to electron current. Such circuit exploits nano-magnetic nodes as spin-polarized carries injectors and non-magnetic channel as spin transporter between these nano-magnetic nodes. From point of view Physics, Nano- magnetic node is defined as a collection of physical points in a device or a circuit where all the quantities of interest for spin and charge transport are at equilibrium (Žutić, et al., 2004). Non-magnetic channel connects two nano-magnetic nodes. Spin circuit obeys spin ohm's law and spin circuit theory.

a) Spin Ohm's Law

In compared with usual ohm's law, Spin ohm's law shows linear relation between spin current and spin voltage difference vector. Mathematical form of this law is (Brataas, et al., 2000)

$$\vec{I}_s = G\Delta\vec{V}_s \qquad (1)$$

Where $\vec{I}_s$, G, $\Delta\vec{V}_s$ are spin current vector, spin conduction matrix and spin voltage vector, respectively. Spin current and spin voltage vector are 3*1 matrixes. The latter exists due to creation of spin polarized population in the nano- magnetic node. Spin conduction matrix is defined as 3*3 matrix proportionality constant which relates spin current vector to spin voltage difference vector and it can be written as (Brataas, et al., 2000):

$$G = \begin{bmatrix} G_{11} & G_{12} & G_{13} \\ G_{21} & G_{22} & G_{23} \\ G_{31} & G_{32} & G_{33} \end{bmatrix} \qquad (2)$$

Spin current vector in a branch of a spin circuit can be represented as

$$\vec{I}_s = \begin{bmatrix} I_{sx} \\ I_{sy} \\ I_{sz} \end{bmatrix} \qquad (3)$$

Where I_{sx}, I_{sy} and I_{sz} is vector spin current components along x-direction, y- direction and z-direction, respectively. Mathematical form spin voltage vector describe as

$$\vec{V}_s = \begin{bmatrix} V_{sx} \\ V_{sy} \\ V_{sz} \end{bmatrix} \qquad (4)$$

Where V_{sx}, V_{sy} and V_{sz} is spin voltage vector components along x- direction, y- direction and z-direction, respectively.

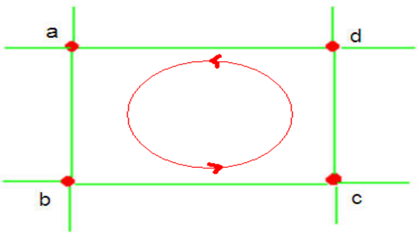
b) Kirchhoff's Laws

In a linear spin circuit, sum of voltage differences in any closed loop is zero (Fig. 1). This well-known law is called Kirchhoff's voltage law and is written as below form (Brataas, et al., 2000):

$$\sum_{a,b\epsilon A}\left(V_{s,a} - V_{s,b}\right) = 0 \qquad (5)$$

Where $V_{s,a}$ and $V_{s,b}$ are spin voltage vector in (a) and (b), respectively.

Fig-1. Schematic of closed loop for Kirchhoff's voltage law.

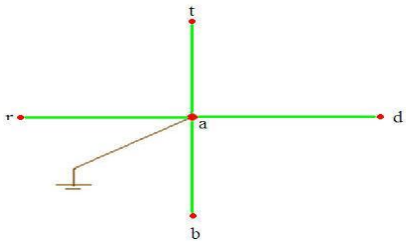


Since spin currents are non-conservative, we must consider spin dissipation current to the virtual ground (Srinivasan, et al., 2011). In a linear spin circuit, Kirchhoff's current law says sum of the spin currents vector entering node is equal to total dissipated spin current vector from it. Mathematical form of such law is presented as (Brataas, et al., 2000)

$$\sum_{x\epsilon C}\left(\vec{I}_{s,ax}-\vec{I}_{s,da}\right)=0 \qquad (6)$$

Where $\vec{I}_{s,ax}$ is spin current vector from (a) to (x) node and $\vec{I}_{s,da}$ is total spin current vector dissipated due to spin-flip events occurring at node. Fig. 2 shows a schematic which help us to write Kirchhoff's current law for (a) node.

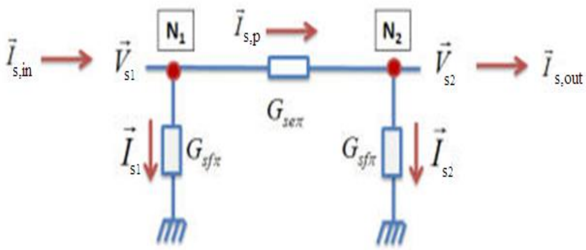
Fig-2. Schematic of Kirchhoff's current law.



3. Calculation of Spin Current in Π-Shaped Spin Circuit

In this section, we intend to calculate spin current in Π-shaped spin circuit. As shown in Fig.3, our spin circuit consisting of two nano-magnetic nodes, N_1 and N_2, connected by a non-magnetic channel with cross section area A, resistivity ρ, length L, spin-flip length of the channel material λ. Spin-flip branches model dissipation of spin current from the channel due to spin flip process which goes to spin voltage ground.

Fig-3. Π-shaped spin circuit with two nano-magnetic nodes and a non-magnetic channel.



According to Kirchhoff's current law, it's necessary to write relation between the spin current vectors entering nodes and the total dissipated spin current vector at nodes as below (Brataas, et al., 2000):

$$\vec{I}_{s,in}=\vec{I}_{sp}-\vec{I}_{s1} \qquad (7)$$

$$\vec{I}_{s,out}=\vec{I}_{sp}+\vec{I}_{s2} \qquad (8)$$

Where $\vec{I}_{s,in}$ $\left(\vec{I}_{s,out}\right)$ is spin current entering N_1 (exiting N_2). $\vec{I}_{sp}$ is spin current flowing in series branch. $\vec{I}_{s1}$ and $\vec{I}_{s2}$ are dissipated spin currents which are flowed in spin-flip branches. $G_{se\pi}$ $(G_{sf\pi})$ determines spin conduction matrix of series branch (spin-flip branches) and their mathematical form can be represented as (Behin-Aein, et al., 2011) and (Srinivasan, et al., 2011).

$$G_{se\pi}=\begin{bmatrix}\frac{A}{\rho\lambda}\operatorname{csch}\frac{L}{\lambda} & 0 & 0\\ 0 & \frac{A}{\rho\lambda}\operatorname{csch}\frac{L}{\lambda} & 0\\ 0 & 0 & \frac{A}{\rho\lambda}\operatorname{csch}\frac{L}{\lambda}\end{bmatrix} \qquad (9)$$

$$G_{sf\pi} = \begin{bmatrix} \frac{A}{\rho\lambda}\tanh\frac{L}{2\lambda} & 0 & 0 \\ 0 & \frac{A}{\rho\lambda}\tanh\frac{L}{2\lambda} & 0 \\ 0 & 0 & \frac{A}{\rho\lambda}\tanh\frac{L}{2\lambda} \end{bmatrix} \qquad (10)$$

Where rows of matrices demonstrate spin conductance along x, y and z direction, respectively. Note that there is no distinction between rows for non-magnetic materials. According to drift-diffusion equation, spin voltage is (Behin-Aein, et al., 2011)

$$V_s = e^{(-x/\lambda)} \qquad (11)$$

Thus spin voltage vector of N_1 and N_2 nodes can write as below

$$\vec{V}_{s1} = \begin{bmatrix} e^{(L/2\lambda)} \\ e^{(L/2\lambda)} \\ e^{(L/2\lambda)} \end{bmatrix}, \ \vec{V}_{s2} = \begin{bmatrix} e^{(-L/2\lambda)} \\ e^{(-L/2\lambda)} \\ e^{(-L/2\lambda)} \end{bmatrix} \qquad (12)$$

We assume that this spin circuit has symmetric geometry and spin voltage vector's components are equal. By using equations (1), (9) and (12), we rewrite spin ohm's law for series branch as

$$\begin{cases} I_{sp,x} = \frac{A}{\rho\lambda}\operatorname{csch}\frac{L}{\lambda}\left(e^{(-L/2\lambda)} - e^{(L/2\lambda)}\right) \\ I_{sp,y} = \frac{A}{\rho\lambda}\operatorname{csch}\frac{L}{\lambda}\left(e^{(-L/2\lambda)} - e^{(L/2\lambda)}\right) \\ I_{sp,z} = \frac{A}{\rho\lambda}\operatorname{csch}\frac{L}{\lambda}\left(e^{(-L/2\lambda)} - e^{(L/2\lambda)}\right) \end{cases} \qquad (13)$$

Where $e^{(-L/2\lambda)} - e^{(L/2\lambda)}$ is spin voltage difference vector's component. Therefore spin current vector of series branch can be represented as

$$\vec{I}_{sp} = \frac{A}{\rho\lambda}\operatorname{csch}\frac{L}{\lambda}\left(e^{(-L/2\lambda)} - e^{(L/2\lambda)}\right)[\hat{x} + \hat{y} + \hat{z}] \qquad (14)$$

And its value is

$$I_{sp} = \frac{\sqrt{3}A}{\rho\lambda}\operatorname{csch}\frac{L}{\lambda}\left(e^{(-L/2\lambda)} - e^{(L/2\lambda)}\right) \qquad (15)$$

For first spin-flip branch, spin ohm's law is written by using equations (1), (10) and (12) as

$$\begin{cases} I_{s1,x} = \frac{A}{\rho\lambda}e^{(L/2\lambda)}\tanh\frac{L}{2\lambda} \\ I_{s1,y} = \frac{A}{\rho\lambda}e^{(L/2\lambda)}\tanh\frac{L}{2\lambda} \\ I_{s1,z} = \frac{A}{\rho\lambda}e^{(L/2\lambda)}\tanh\frac{L}{2\lambda} \end{cases} \qquad (16)$$

Where $e^{(L/2\lambda)}$ is spin voltage difference vector's component. Therefore spin current vector of first spin-flip branch can be represented as

$$\vec{I}_{s1} = \frac{A}{\rho\lambda}e^{(L/2\lambda)}\tanh\frac{L}{2\lambda}[\hat{x} + \hat{y} + \hat{z}] \qquad (17)$$

And its value is

$$I_{s1} = \frac{\sqrt{3}A}{\rho\lambda}e^{(L/2\lambda)}\tanh\frac{L}{2\lambda} \qquad (18)$$

Also spin ohm's law for second spin-flip branch is as

$$\begin{cases} I_{s2,x} = \frac{A}{\rho\lambda}e^{(-L/2\lambda)}\tanh\frac{L}{2\lambda} \\ I_{s2,y} = \frac{A}{\rho\lambda}e^{(-L/2\lambda)}\tanh\frac{L}{2\lambda} \\ I_{s2,z} = \frac{A}{\rho\lambda}e^{(-L/2\lambda)}\tanh\frac{L}{2\lambda} \end{cases} \qquad (19)$$

Where $e^{(-L/2\lambda)}$ is spin voltage difference vector's component. Therefore spin current vector of this branch can be represented as

$$\vec{I}_{s2} = \frac{A}{\rho\lambda}e^{(-L/2\lambda)}\tanh\frac{L}{2\lambda}[\hat{x} + \hat{y} + \hat{z}] \qquad (20)$$

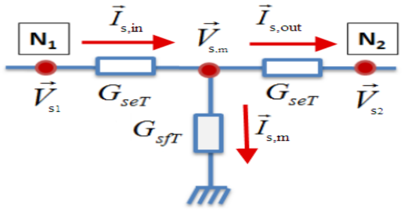
And its value is

$$I_{s2} = \frac{\sqrt{3}A}{\rho\lambda}e^{(L/2\lambda)}\tanh\frac{L}{2\lambda} \qquad (21)$$

4. Calculation of Spin Current in T-Shaped Spin Circuit

By conversion a Π-shaped spin circuit to those of T-shaped, we intend to compute spin current vector in all branches of it (Fig. 4).

Fig-4. T-shaped spin circuit with two nano-magnetic nodes and a non-magnetic channel.



In T-shaped spin circuit, we have middle node which goes to virtual ground. According to Kirchhoff's current, spin current vectors entering middle node and the total dissipated spin current vector at this node as below

$$\vec{I}_{s,out} = \vec{I}_{s,in} + \vec{I}_{s,m} \qquad (22)$$

Where $\vec{I}_{s,m}$ is total dissipated spin current from middle node. Mathematical forms of $\vec{I}_{s,out}$ and $\vec{I}_{s,in}$ are

$$\vec{I}_{s,out} = G_{seT}(\vec{V}_{s,m} - \vec{V}_{s1}) \qquad (23)$$

$$\vec{I}_{s,in} = G_{seT}(\vec{V}_{s2} - \vec{V}_{s,m}) \qquad (24)$$

Where $\vec{V}_{s,m}$ spin voltage vector of middle node which is calculated by equations 7, 8 and (21) – (13) as

$$\vec{V}_{s,m} = \left(e^{\left(\frac{L}{2\lambda}\right)} + e^{\left(-\frac{L}{2\lambda}\right)}\right)\frac{\operatorname{csch}\frac{L}{\lambda}}{\tanh\frac{L}{2\lambda}+2\operatorname{csch}\frac{L}{\lambda}}\begin{bmatrix}1\\1\\1\end{bmatrix} \qquad (25)$$

Note that $\vec{I}_{s,in}$ and $\vec{I}_{s,out}$ in two types of spin circuits are the same. By considering matrices (9) and (10), spin conduction matrices of series and spin-flip branches of T-shaped spin circuit as

$$G_{seT} = \frac{A}{\rho\lambda}\left[2\operatorname{csch}\frac{L}{\lambda} + \tanh\frac{L}{2\lambda}\right]\begin{bmatrix}1 & 0 & 0\\0 & 1 & 0\\0 & 0 & 1\end{bmatrix} \qquad (26)$$

$$G_{sfT} = \frac{A\tanh\frac{L}{2\lambda}}{\rho\lambda}\left(\frac{\tanh\frac{L}{2\lambda}}{\operatorname{csch}\frac{L}{\lambda}} + 2\right)\begin{bmatrix}1 & 0 & 0\\0 & 1 & 0\\0 & 0 & 1\end{bmatrix} \qquad (27)$$

Where rows of matrices demonstrate spin conductance along three directions. By using equations (1), (12), (25) and (26), spin ohm's law for first series branch calculate as

$$\begin{cases} I_{sx,in} = \frac{A}{\rho\lambda}\left[e^{\left(-\frac{L}{2\lambda}\right)}\operatorname{csch}\frac{L}{\lambda} - e^{\left(\frac{L}{2\lambda}\right)}\left(\operatorname{csch}\frac{L}{\lambda} + \tanh\frac{L}{2\lambda}\right)\right] \\ I_{sy,in} = \frac{A}{\rho\lambda}\left[e^{\left(-\frac{L}{2\lambda}\right)}\operatorname{csch}\frac{L}{\lambda} - e^{\left(\frac{L}{2\lambda}\right)}\left(\operatorname{csch}\frac{L}{\lambda} + \tanh\frac{L}{2\lambda}\right)\right] \\ I_{sz,in} = \frac{A}{\rho\lambda}\left[e^{\left(-\frac{L}{2\lambda}\right)}\operatorname{csch}\frac{L}{\lambda} - e^{\left(\frac{L}{2\lambda}\right)}\left(\operatorname{csch}\frac{L}{\lambda} + \tanh\frac{L}{2\lambda}\right)\right] \end{cases} \qquad (28)$$

Therefore spin current vector of this branch can be represented as

$$\vec{I}_{s,in} = \frac{A}{\rho\lambda}\left[e^{\left(-\frac{L}{2\lambda}\right)}\operatorname{csch}\frac{L}{\lambda} - e^{\left(\frac{L}{2\lambda}\right)}\left(\operatorname{csch}\frac{L}{\lambda} + \tanh\frac{L}{2\lambda}\right)\right][\hat{x} + \hat{y} + \hat{z}] \qquad (29)$$

And its value is

$$I_{s,in} = \frac{\sqrt{3}A}{\rho\lambda}\left[e^{\left(-\frac{L}{2\lambda}\right)}\operatorname{csch}\frac{L}{\lambda} - e^{\left(\frac{L}{2\lambda}\right)}\left(\operatorname{csch}\frac{L}{\lambda} + \tanh\frac{L}{2\lambda}\right)\right] \qquad (30)$$

Also spin ohm's law for second series branch is as

$$\begin{cases} I_{sx,out} = \frac{A}{\rho\lambda}\left[e^{\left(-\frac{L}{2\lambda}\right)}\left(\operatorname{csch}\frac{L}{\lambda} + \tanh\frac{L}{2\lambda}\right) - e^{\left(\frac{L}{2\lambda}\right)}\operatorname{csch}\frac{L}{\lambda}\right] \\ I_{sy,out} = \frac{A}{\rho\lambda}\left[e^{\left(-\frac{L}{2\lambda}\right)}\left(\operatorname{csch}\frac{L}{\lambda} + \tanh\frac{L}{2\lambda}\right) - e^{\left(\frac{L}{2\lambda}\right)}\operatorname{csch}\frac{L}{\lambda}\right] \\ I_{sz,out} = \frac{A}{\rho\lambda}\left[e^{\left(-\frac{L}{2\lambda}\right)}\left(\operatorname{csch}\frac{L}{\lambda} + \tanh\frac{L}{2\lambda}\right) - e^{\left(\frac{L}{2\lambda}\right)}\operatorname{csch}\frac{L}{\lambda}\right] \end{cases} \qquad (31)$$

Spin current vector of this branch is as

$$\vec{I}_{s,out} = \frac{A}{\rho\lambda}\left[e^{\left(-\frac{L}{2\lambda}\right)}\left(\operatorname{csch}\frac{L}{\lambda} + \tanh\frac{L}{2\lambda}\right) - e^{\left(\frac{L}{2\lambda}\right)}\operatorname{csch}\frac{L}{\lambda}\right][\hat{x} + \hat{y} + \hat{z}] \qquad (32)$$

And its value is

$$I_{s,out} = \frac{\sqrt{3}A}{\rho\lambda}\left[e^{\left(-\frac{L}{2\lambda}\right)}\left(\operatorname{csch}\frac{L}{\lambda} + \tanh\frac{L}{2\lambda}\right) - e^{\left(\frac{L}{2\lambda}\right)}\operatorname{csch}\frac{L}{\lambda}\right] \qquad (33)$$

Now, we want to compute spin current vector in spin-flip branch. Using spin ohm's law for this branch, spin current vector is

$$\begin{cases} I_{sm,x} = \frac{A}{\rho\lambda}\left(e^{(\frac{L}{2\lambda})} + e^{(-\frac{L}{2\lambda})}\right)\tanh\frac{L}{2\lambda} \\ I_{sm,y} = \frac{A}{\rho\lambda}\left(e^{(\frac{L}{2\lambda})} + e^{(-\frac{L}{2\lambda})}\right)\tanh\frac{L}{2\lambda} \\ I_{sm,z} = \frac{A}{\rho\lambda}\left(e^{(\frac{L}{2\lambda})} + e^{(-\frac{L}{2\lambda})}\right)\tanh\frac{L}{2\lambda} \end{cases} \quad (34)$$

Thus spin current vector can be represented as

$$\vec{I}_{s,m} = \frac{A}{\rho\lambda}\left(e^{(\frac{L}{2\lambda})} + e^{(-\frac{L}{2\lambda})}\right)\tanh\frac{L}{2\lambda}[\hat{x} + \hat{y} + \hat{z}] \quad (35)$$

And its value is

$$I_{s,m} = \frac{\sqrt{3}A}{\rho\lambda}\left(e^{(\frac{L}{2\lambda})} + e^{(-\frac{L}{2\lambda})}\right)\tanh\frac{L}{2\lambda} \quad (36)$$

5. Effects of Nano-Channel Length and Cross Section Area Variations on Spin Current

By using experimental data for copper and gold as nano-channel and permalloy as nano-magnetic nodes (Žutić, et al., 2004), spin current has been obtained by taking into account simultaneously effect cross section area and length and results are shown. Figs. 5 and 6 show spin current versus simultaneous variations of cross section area and length nano-channels for series branch of Π-shaped spin circuit. As it comes from this Fig, dark red and blue areas demonstrate highest and lowest spin current values, respectively.

Fig-5. Spin current versus simultaneous variations of cross section area and length of copper nano-channel for series branch of Π-shaped spin circuit.

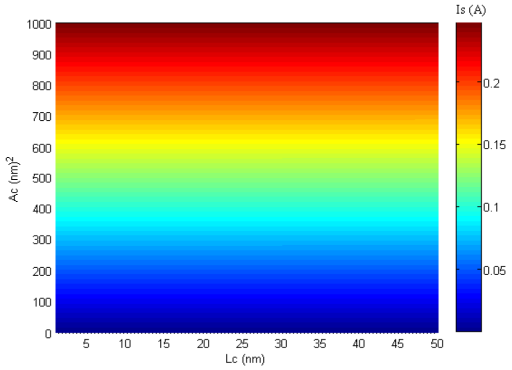
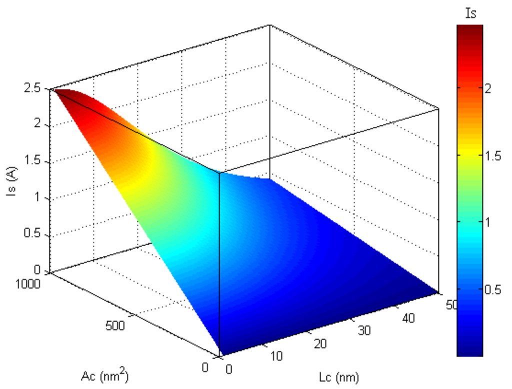


Fig-6. Spin current versus simultaneous variations of cross section area and length of gold nano-channel for series branch of Π-shaped spin circuit.



According to Fig. 5, length variations have modest effect on spin current reduction while increase of cross section area lead to spin current grow up. In Fig. 6, spin current is increase when length is reduced and cross section area grows up. Figs. 7 and 8 represent two dimensional view of such above variations.

Fig-7. Spin current versus variations of copper nano-channel length per five various cross section areas for series branch of Π-shaped spin circuit.

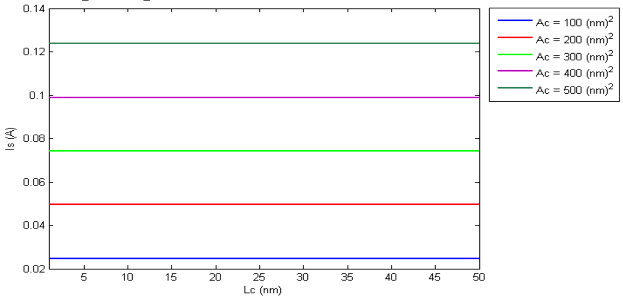
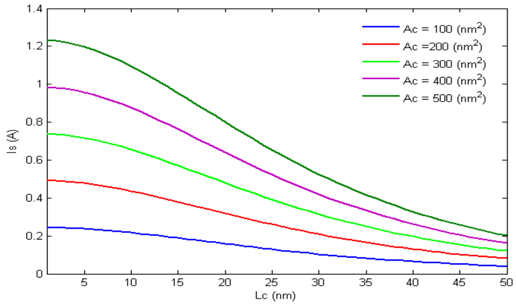


Fig-8. Spin current versus variations of gold nano-channel length per five various cross section areas for series branch of Π-shaped spin circuit.



As show in Fig. 8, we observe spin current reduction per rising length of gold nano-channel for specific cross section area. Figs. 9 and 10 show dissipated spin current versus nano-channels cross section area and length variation for spin-flip branch of Π-shaped spin circuit.

Fig-9. Dissipated spin current versus simultaneous variations of cross section area and length of copper nano-channel for the first spin-flip branch of Π-shaped spin circuit.

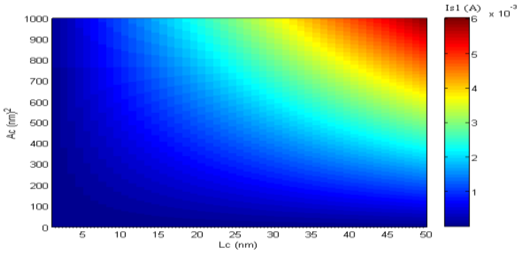
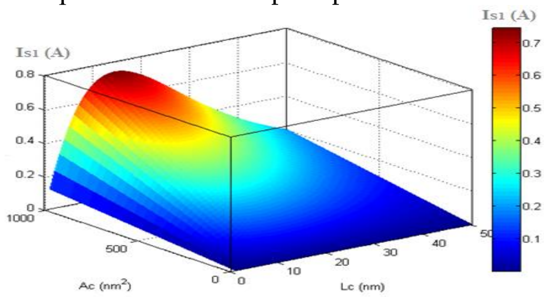


Fig-10. Dissipated spin current versus simultaneous variations of cross section area and length of gold nano-channel for the first spin-flip branch of Π-shaped spin circuit.



According to Figs. 9 and 10, dissipated spin current decrease by cross section area and length reduction. Based on result, because of large copper spin diffusion length, dissipated spin current of gold is larger than that of copper.

Fig-11. Dissipated spin current versus simultaneous variations of cross section area and length of copper nano-channel for the second spin-flip branch of Π-shaped spin circuit.

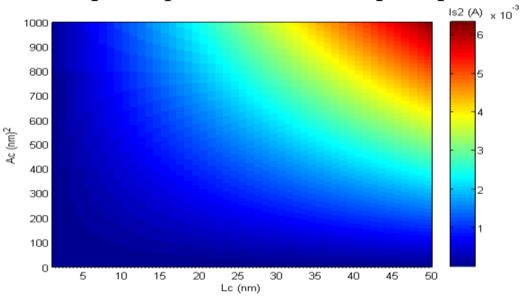
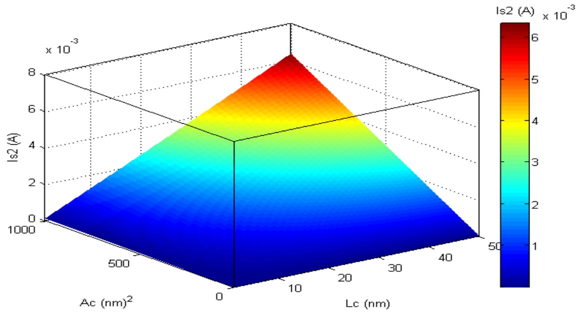


Fig-12. Dissipated spin current versus simultaneous variations of cross section area and length of gold nano-channel for the second spin-flip branch of Π-shaped spin circuit.



As shown in Figs 11 and 12, dissipated spin current of first spin-flip branch is larger than those of second because of spin diffusion length. Also, Figs. 13-16 justify these results.

Fig-13. Dissipated spin current versus variations length of copper nano-channel for five various cross section areas related to the first spin-flip branch of Π-shaped spin circuit.

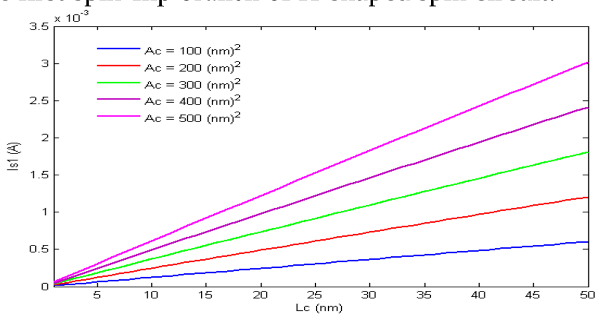


Fig-14. Dissipated spin current versus variations length of gold nano-channel for five various cross section areas related to the first spin-flip branch of Π-shaped spin circuit.

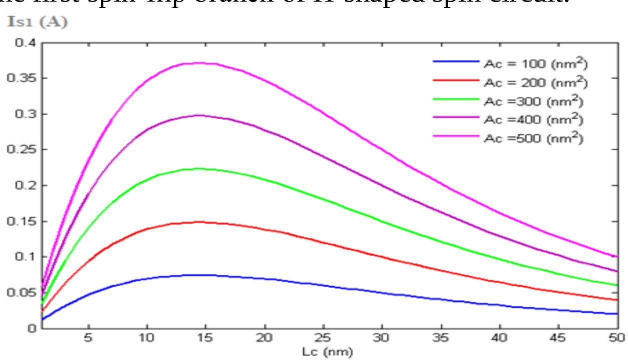


Fig-15. Dissipated spin current versus variations length of copper nano-channel for five various cross section areas related to the second spin-flip branch of Π-shaped spin circuit.

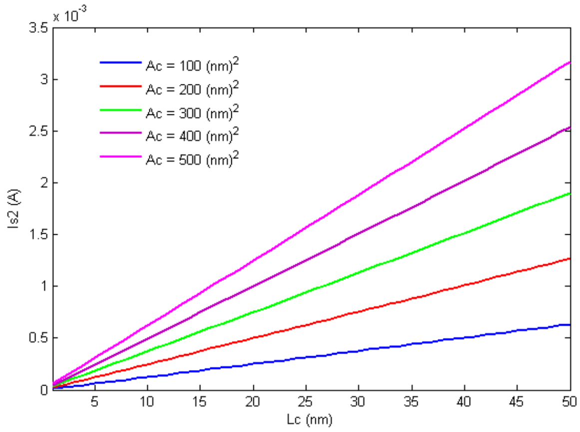
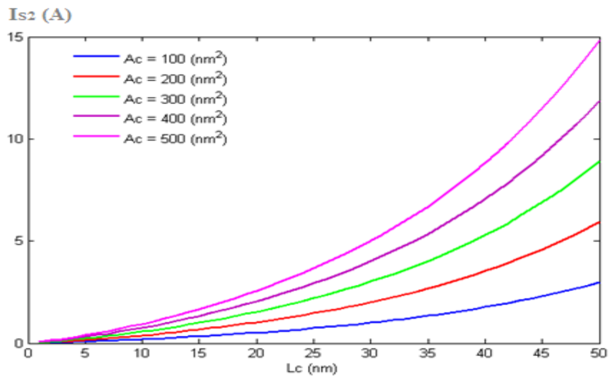


Fig-16. Dissipated spin current versus variations length of gold nano-channel for five various cross section areas related to the second spin-flip branch of Π-shaped spin circuit.



As shown in Figs. 13-16, dissipated spin current decreases by length reduction per specific cross section area. Figs. 17 and 18 shows spin current versus nano-channels cross section area and length variations for the first series branch of T-shaped spin circuit.

Fig-17. Spin current versus simultaneous copper nano-channel length and cross section area variations related to the first series branch of T-shaped spin circuit.

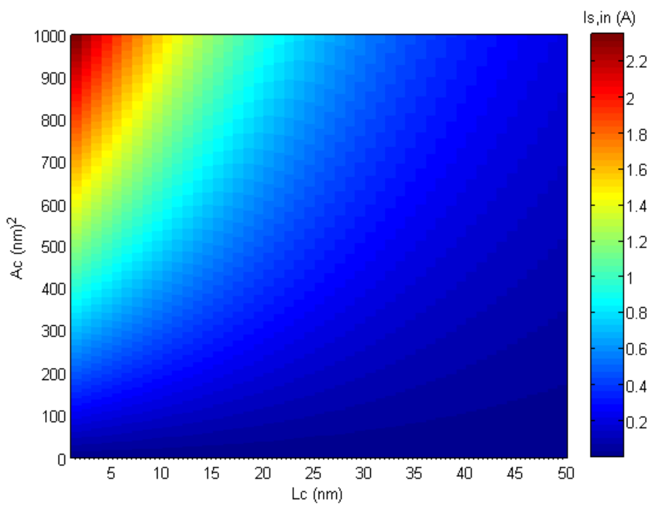
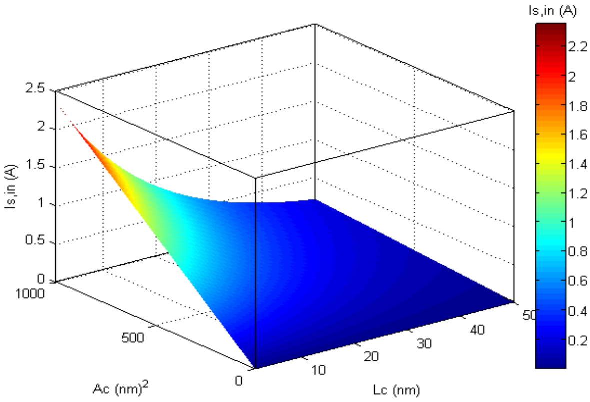


Fig-18. Spin current versus simultaneous gold nano-channel length and cross section area variations related to the first series branch of T-shaped spin circuit.



According to Figs. 17 and 18, spin current increases by simultaneously length reduction and cross section area grow up. Figs. 19 and 20 represent two dimensional view of such variations.

Fig-19. Spin current versus copper nano-channel length and cross section area variation for five various cross section area related to the first series branch of T-shaped spin circuit.

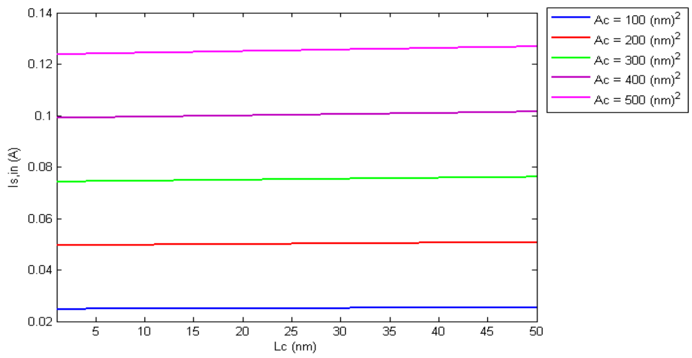
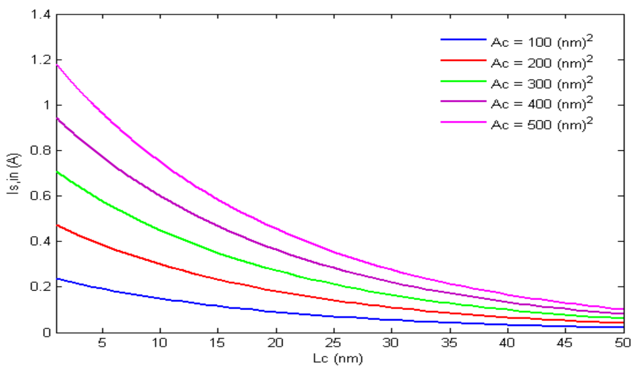


Fig-20. Spin current versus gold nano-channel length and cross section area variation for five various cross section area related to the first series branch of T-shaped spin circuit.



Based on Figs. 19 and 20, spin current of copper nano-channel increases by length grow up per specific cross section area While spin current of gold nano-channel increases by length reduction per specific cross section area.

Figs. 21 and 22 show spin current versus nano-channels cross section area and length variations for the second series branch of T-shaped spin circuit. Figs. 23 and 24 show dissipated spin current versus the same variations for the spin-flip branch of T-shaped spin circuit.

Fig-21. Spin current versus simultaneous copper nano-channel length and cross section area variations related to the second series branch of T-shaped spin circuit.

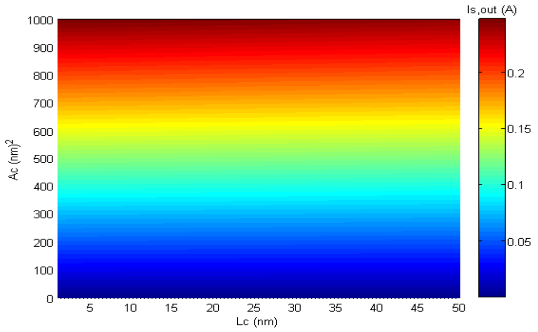


Fig-22. Spin current versus simultaneous gold nano-channel length and cross section area variations related to the second series branch of T-shaped spin circuit.

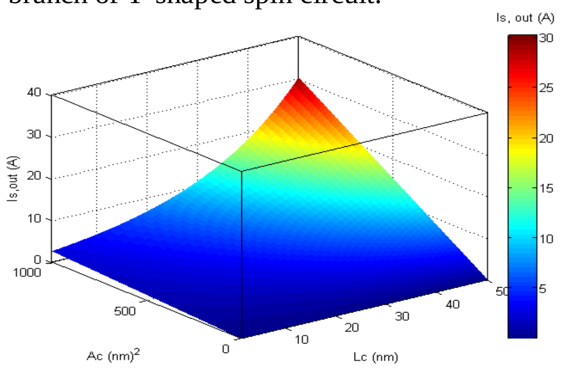


Fig-23. Dissipated spin current versus simultaneous copper nano-channel length and cross section area variations related to the spin-flip branch of T-shaped spin circuit.

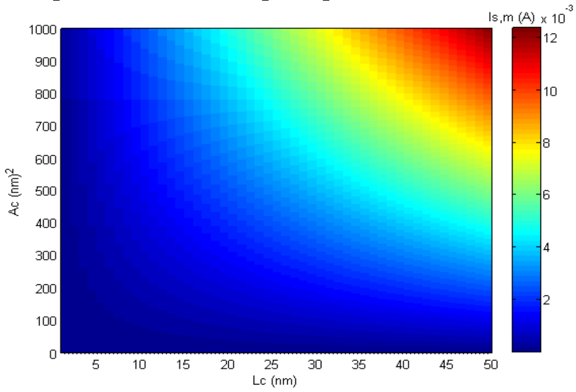
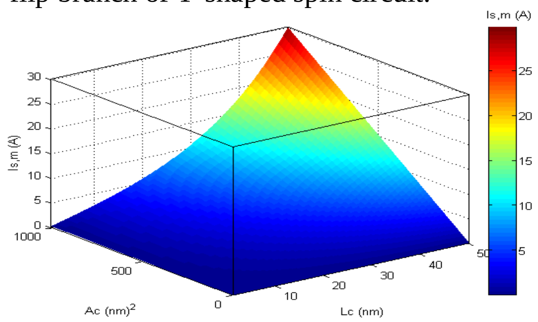


Fig-24. Dissipated spin current versus simultaneous gold nano-channel length and cross section area variations related to the spin-flip branch of T-shaped spin circuit.



According to Fig. 21, spin current of copper nano-channel increase by rise of cross section area and length for the series branch of T-shaped spin circuit. As opposed to gold nano-channel spin current which is grows by cross section area and length rise. Based on Figs. 23 and 24, dissipated spin current reduction occurs when we decrease cross section area and length. Also, Figs. 25 and 26 justify these results.

Fig-25. Spin current versus copper nano-channel length variations for five various cross section areas related to the second series branch of T-shaped spin circuit.

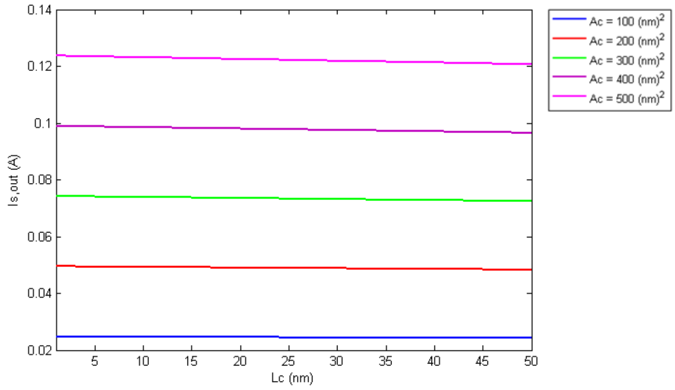


Fig-26. Spin current versus gold nano-channel length variations for five various cross section areas related to the second series branch of T-shaped spin circuit.

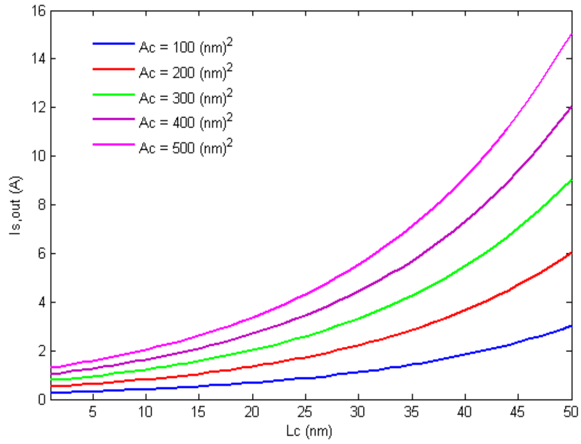


Fig-27. Dissipated spin current versus copper nano-channel length variations for five various cross section areas related to spin-flip branch of T-shaped spin circuit.

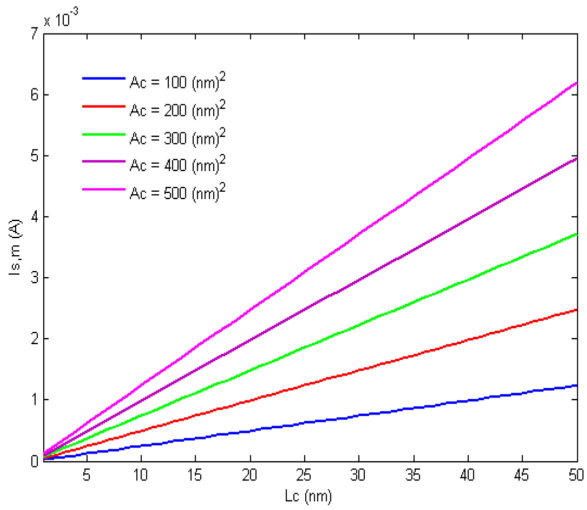
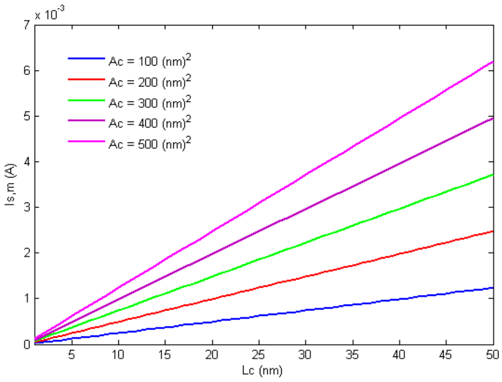


Fig-28. Dissipated spin current versus gold nano-channel length variations for five various cross section areas related to spin-flip branch of T-shaped spin circuit.



As show in Figs. 27 and 28, spin current grows up by length reduction for specific cross section area. Table 1 is illustrated obtained values for spin currents of spin circuit's branches.

Table-1. Obtained values for spin currents of nano-channels related to two branches of Π-shaped spin circuit.

Variants		**spin-flip branch**				**Series branch**	
L	**A**	**I_{s1}**		**I_{s2}**		**I_{sp}**	
(nm)	**$(nm)^2$**	**Cu**	**Au**	**Cu**	**Au**	**Cu**	**Au**
20	100	0.0002	0.06	0.0002	0.51	0.03	0.16
30	400	0.0014	0.19	0.0015	4.02	0.1	0.41
50	500	0.0030	0.1	0.0031	14.87	0.13	0.2

Table-2. Obtained values for spin currents of nano-channels related to two branches of T-shaped spin circuit.

Variants		**Series branch**				**spin-flip branch**	
L	**A**	**$I_{s,in}$**		**$I_{s,out}$**		**$I_{s,Md}$**	
(nm)	**$(nm)^2$**	**Cu**	**Au**	**Cu**	**Au**	**Cu**	**Au**
20	100	0.02	0.09	0.26	0.67	0.004	0.58
30	400	0.09	0.22	1.64	4.43	0.002	4.21
50	500	0.12	0.1	2.30	15.07	0.006	14.97

7. Conclusion and Discussion

In this paper, we saw that spin current in series branch increases when we have nano-channel length reduction and nano channel cross section area grow up. As spin current in spin-flip branch shows spin polarization dissipation, we prefer to lower it. We can reduce spin current of this branch simultaneously decrease of nano-channel length and cross section area. We investigate two different non-magnetic channels (copper and gold) as nano channel. We prefer copper metal choice as nano-channel because of longer spin diffusion length, less spin current dissipation and equality of its lattice constant with those of permalloy.

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