Indian Journal of Fundamental and Applied Life Sciences ISSN: 2231– 6345 (Online)
An Open Access, Online International Journal Available at www.cibtech.org/sp.ed/jls/2015/02/jls.htm
2015 Vol. 5 (S2), pp. 467-471/Vafaie et al.
Research Article

THE IMPACT OF SUBSTITUTING A SUPERCONDUCTOR WITH THE NORMAL METAL ON CHARGE TRANSPORT PROPERTIES IN THE CONNECTIONS INCLUDING SHARP FERROMAGETIC DOMAIN-WALL

***Rouhollah Vafaie[1], Davood Pourmostafa[2] and Kheirollah Khodayari[3]**
[1]Department of Physics, Shahindej Branch, Islamic Azad University, Shahindej, Iran
[2]Department of Physics, Khoy Branch, Islamic Azad University, Khoy, Iran
[3]Department of Physics, Tabriz Branch, Islamic Azad University, Tabriz, Iran
**Author for Correspondence*

ABSTRACT
Using the scattering matrix and Landauer- Buttiker formulation, this study aimed to investigate the conductance of a mesoscopic connection including normal metal connection to two ferromagnetic domains of non- collinear magnetizations. It was shown that with increasing the angle between the magnetizations of two joint domains, the conductivity steadily decreased. Also, the results showed that the conductivity curve indicated a maximum, in terms of angle, in the angle which depended on exchange energy magnitude by substituting a superconductor with the normal metal.

Keywords: *Ferromagnetic Domain-Wall, Superconductor, Bogoliobove De-Gennes Equation, Andrriv Reflection*

INTRODUCTION
Because of the added vectors spin' degrees of freedom to the parameters affecting the transport of charge in connections including ferromagnetic and the possibility of using spin currents in quantum connections for creating spin polarized current, these types of connections are of great concern in recent years (Zutic *et al.,* 2004; Shomali *et al.,* 2008; Maleki and Zareyan, 2006).
In previous research, the transport behavior of systems composed of ferromagnetic, superconducting, and normal metal have been studied extensively (Shomali *et al.*, 2008; Maleki and Zareyan, 2006; Klapwijk *et al.*, 1999).
The ferromagnetic order causes vector spins orient in a particular direction. So, the ferromagnetic in a connection induces a parallel arrangement in spins (Maleki and Zareyan, 2006). By increasing the amount of energy exchange in a system which includes normal metal and ferromagnetic, the conductance is reduced due to the reduction of available modes for lower spins (the opposite spin direction for magnetization of the ferromagnetic).
Depending on the spin state of the electron like quasi-particle, there are two types of superconductors: single spin and triple spin. This classification indicates the type of spin coupling of Cooper pair which affects the charge transport in the superconductor (Maleki and Zareyan, 2006; Klapwijk *et al.,* 1999). It has been observed that when ferromagnetic is in the vicinity of superconductor, there will be spin triplet superconductivity states in the system, while the magnetization of the ferromagnetic area is non-parallel and heterogeneous (Maleki and Zareyan, 2006; Klapwijk *et al.*, 1999).
This paper aims to investigate a system which consists of a normal metal and is connected to two ferromagnetic domains in which the vector direction of magnetization is different. Also, it studies the dependency of conductivity on angle changes in the magnetization vectors in two adjacent areas. The results, finally, will be compared with the results of same connection where there is a single spin superconductor instead of normal metal (Kashisaz and Zare'ian).

Model and Approach
We model the FFN connection as follows; where, FL and FR represent the ferromagnetic domains with uniform and constant magnetization and N indicates normal metal (non magnetic and non-superconductor).

Research Article

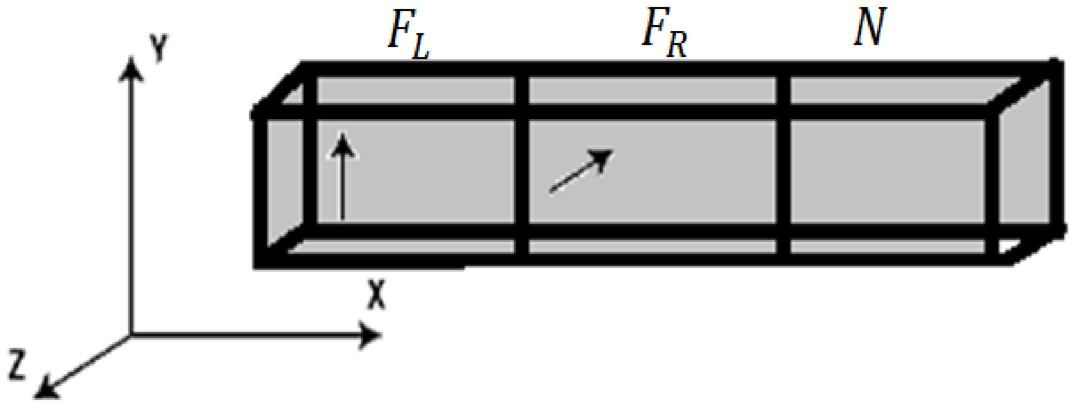

Figure 1: FFS connection

In the ferromagnetic areas and also in the normal metal area, Schrödinger equation is used to describe wave function of vectors (Equation 1).

$$\begin{pmatrix} \frac{P^2}{2m} - E_F - \frac{\Delta}{2} & 0 \\ 0 & \frac{P^2}{2m} - E_F - \frac{\Delta}{2} \end{pmatrix} \begin{pmatrix} \varphi_M^{\uparrow} \\ \varphi_M^{\downarrow} \end{pmatrix} = \varepsilon \begin{pmatrix} \varphi_M^{\uparrow} \\ \varphi_M^{\downarrow} \end{pmatrix} \qquad (1)$$

In this equation, $\frac{p^2}{2m}$is the electron kinetic energy in the area M; M represents the area of interest (M= {F_L, F_R, N}).Δ is the exchange energy in the ferromagnetic areas. E_F is the Fermi energy of normal state. Also, ε is the vectors energy relative to the Fermi energy level ($\varepsilon = E - E_f$). We assume that the system is connected from the normal metal to positive voltage and from the left side to negative voltage. Considering very small voltages compared with the Fermi energy ($\varepsilon = eV \ll E_f$), we study the conductance behavior of system (Kashisaz and Zare'ian; De Jang and Seenekker, 1995). Solving the Schrödinger equation in the normal metal area as well as in the ferromagnetic areas, the wave function is obtained in all three areas. In solving the equations, the two electron spin states incident from the left ferromagnetic area are separately reviewed (Zutic *et al.*, 2004; Kashisaz and Zare'ian; De Jang and Seenekker, 1995). When an incident electron spin is being higher than left ferromagnetic, the wave function in each three areas at the normal spin bases will be obtained as follows:

$$\varphi_{FL} = \text{x-}Fe^{-ik^{\downarrow}x} r^{\uparrow\downarrow} + e_{X+F}{}^{-ik^{2}X} r^{\uparrow} + e^{ik^{\uparrow}x}_{X+F} \qquad (2)$$

$$C_l = \text{x-FD}_2 e^{ik^{\downarrow}x} + \text{x+FC}_2 e^{-ik^{\uparrow}x} + \text{x-Fe}^{ik^{\downarrow}x}\text{D}_\text{l} + \text{x+F}e^{ik^{\uparrow}x} \varphi_{Fn} \qquad (3)$$

$$\varphi_N = \text{x-N}e^{ikx} x + N \pm \text{t}^{\downarrow\uparrow} e^{ikx} t^{\uparrow\uparrow} \qquad (4)$$

Similar equations are written for low-spin state of incident electron. The proportional wave vector size of each state is obtained from solving the value equation in each area.

$$K = \sqrt{\frac{2m}{h^2}\left[E_F - E_n \pm \frac{\Delta}{2}\right]}\,\text{k}^{\uparrow/\downarrow} = \sqrt{\frac{2m}{h^2}\left[E_F + E_n\right]} \qquad (5)$$

En is the energy of electron’s transverse mode. We assume that the wave function transverse section remains continuous in passing through the intersection of any two adjacent areas (Zutic *et al.*, 2004; Kashisaz and Zare'ian). Therefore, the transverse energy of vectors remains constant during the transport$X_{\pm M}$. The Spinors are proportional to the Pauli matrix. We consider that the positive spin direction in each area matches with the local magnetization direction. Also, we consider that the positive spin direction in normal area is parallel to magnetization of right ferromagnetic area. After obtaining the wave functions on the local generalized Spinory bases, the boundary conditions appropriate to the problem are introduced to obtain the reflection and transmission coefficients (Kashisaz and Zare'ian; De Jang and Seenekker, 1995). In applying the continuity condition, the wave function of both adjacent areas should have the same spinory bases. Assuming the adaptation of spinory bases in both normal and

Indian Journal of Fundamental and Applied Life Sciences ISSN: 2231– 6345 (Online)
An Open Access, Online International Journal Available at www.cibtech.org/sp.ed/jls/2015/02/jls.htm
2015 Vol. 5 (S2), pp. 467-471/Vafaie et al.
Research Article

intermediate ferromagnetic areas, therefore, the generalized rotation matrix is used for rotating and matching the two areas by applying the boundary condition at the interface between two ferromagnetic areas:

$$R_{(\theta)} = \begin{pmatrix} \cos\frac{\theta}{2} & \sin\frac{\theta}{2} \\ -\sin\frac{\theta}{2} & \cos\frac{\theta}{2} \end{pmatrix} \tag{6}$$

Applying the boundary conditions, the reflection coefficients are obtained for both states of electron incident spin from the left ferromagnetic area. Using these coefficients, finally, we get the conductance of the system. Then, we consider a similar system in which a single-mode s-wave spin superconductor is placed instead of normal metal. In the presence of superconductor, the Bogoliubov De Zhan (BdG) equation was used to obtain the wave function describing the vectors.

$$\begin{pmatrix} \frac{\mathbf{p}^2}{2m} & \mathbf{0} & \Delta_s & \mathbf{0} \\ \mathbf{0} & \frac{\mathbf{p}^2}{2m}-\mathbf{E}_f & \mathbf{0} & \Delta_s \\ \Delta_s & \mathbf{0} & -\frac{\mathbf{p}^2}{2m}-\mathbf{E}_f & \mathbf{0} \\ \mathbf{0} & \Delta_s & \mathbf{0} & -\frac{\mathbf{p}^2}{2m}-\mathbf{E}_f \end{pmatrix} \begin{pmatrix} \boldsymbol{\varphi}_s^{e\uparrow} \\ \boldsymbol{\varphi}_s^{e\downarrow} \\ \boldsymbol{\varphi}_s^{h\downarrow} \\ \boldsymbol{\varphi}_s^{h\uparrow} \end{pmatrix} = \boldsymbol{\varepsilon} \begin{pmatrix} \boldsymbol{\varphi}_s^{e\uparrow} \\ \boldsymbol{\varphi}_s^{e\downarrow} \\ \boldsymbol{\varphi}_s^{h\downarrow} \\ \boldsymbol{\varphi}_s^{h\uparrow} \end{pmatrix} \tag{7}$$

Where, ε is the excitation energy of quasi-particles relative to Fermi energy of normal state (EF); and $\Delta_{\mathbf{s}}$is the superconducting gap energy. The excitation energy of quasi-particles should be regarded zero to consider all the charge transport from the superconductor as a result of Cooper pairs' formation in the superconductor area (De Jang and Seenekker, 1995). With this assumption, the charge transport takes place only through the mechanism of Andreev reflection (De Jang and Seenekker, 1995; Kashisaz and Zare'ian). The $\boldsymbol{\varphi}_{\mathbf{s}}^{\mathbf{h}\downarrow}$is the hole contribution of wave function with low spin in the superconductor area. For the inside of ferromagnetic, the Schrödinger equation and generalized Hamiltonian to the spin - quasi-particle space is used. It is obtained by considering the value of superconducting gap in equation (7) as zero. Also here, we consider the vectors at the Fermi energy level (0 = ε). As the previous state, the Hamiltonian and wave functions in ferromagnetic areas are written in local normal generalized spinory bases. In these bases, Hamiltonian is diagonal and spin direction is corresponding to the direction of local magnetization (De Jang and Seenekker, 1995; Kashisaz and Zare'ian). Solving the Bogoliubov De Zhan equation in superconductor area and Schrödinger equation in ferromagnetic areas, the wave functions are obtained in all three areas (high spin state for incident electron):

$$\varphi_{FL} = \mathrm{x}^h\text{-F}e^{ik^\downarrow x}\mathrm{x}^h\text{+F} + r_{he}^{\downarrow\uparrow}e^{ik^\uparrow x} \qquad r_{he}^{\uparrow\uparrow}\text{+X}^{\mathrm{e}}\text{- f}e^{-ik^\downarrow x}\mathrm{X}^{\mathrm{e}}\text{+f} + \mathrm{r}_{ee}^{\downarrow\uparrow}e^{-ik^\uparrow x}r_{ee}^{\uparrow\uparrow}\mathrm{X}^{\mathrm{e}}\text{+f} + \mathrm{e}^{ik^\uparrow x} \tag{8}$$

$$\varphi_{FR} = \mathrm{C_l}e^{ik^\uparrow x}\mathrm{X}^{\mathrm{e}}\text{+F} + \mathrm{D_l}e^{ik^\downarrow x}\,\mathrm{X}^{\mathrm{e}}\text{-F} + \mathrm{E_l}e^{-ik^\uparrow x}\,\mathrm{X}^{\mathrm{h}}\text{+F} + \mathrm{F_l}e^{-ik^\downarrow x}\,\mathrm{X}^{\mathrm{h}}-\mathrm{F} + \mathrm{C}_2\,e^{-ik^\uparrow x}\,\mathrm{X}^{\mathrm{e}}\text{+F+ }\mathrm{D}_2\,e^{-ik^\downarrow x}\,\mathrm{X}^{\mathrm{e}}-\mathrm{F} + \mathrm{E}_2e^{ik^\uparrow x}\,\mathrm{X}^{\mathrm{h}}\text{+F+ }\mathrm{F}_2e^{ik^\downarrow x}\,\mathrm{X}^{\mathrm{h}}\text{-F} \tag{9}$$

$$\varphi_s = \mathrm{X}^{\mathrm{h}}\text{- S}e^{-ik_h x}t_{he}^{\uparrow\downarrow}\mathrm{X}^{\mathrm{h}}\text{+S} + e^{-ik_h x}\mathrm{X}^{\mathrm{e}}\text{-S} + t_{he}^{\uparrow\uparrow}e^{ik_e x}\mathrm{t}_{ee}^{\downarrow\uparrow}\,\mathrm{X}^{\mathrm{e}}\text{+S} + e^{ik_e x}\mathrm{t}_{ee}^{\uparrow\uparrow} \tag{10}$$

They are obtained with boundary conditions and obtaining the reflection coefficients. Using Landauer-Büttiker equation, the connection conductance of FFS is obtained at ε = 0 as following (6, 1):

$$\mathrm{G=Tr}\,\frac{e^2}{\pi h}\left[\left|r_{he}^{\uparrow\uparrow}\right| + \left|r_{he}^{\downarrow\uparrow}\right| + \left|r_{he}^{\uparrow\downarrow}\right| + \left|r_{he}^{\downarrow\downarrow}\right|\right] \tag{11}$$

In calculating matrix trace, the sum of all transverse states (open lateral channels) is obtained. Since we assume that the transverse dimensions of system are much larger than the electron Fermi wavelength, the sum of states can be replaced with integration of system's transverse modes energy. The equation of conductivity in FFN system can also be deduced using the conservation of hole- particle from the relation (11). The dependency of FFN system conductivity on the angle between the magnetization of the two adjacent areas is obtained for different values of the exchange energy as is shown in Figure 1. In Figure 1,$\boldsymbol{h_0}=\frac{\Delta}{\mathbf{2E_F}}$, GFFN is the normalized conductance to the normal system conductance. It is assumed that the length of midsection to be $\boldsymbol{\lambda = 10\lambda_F}$.

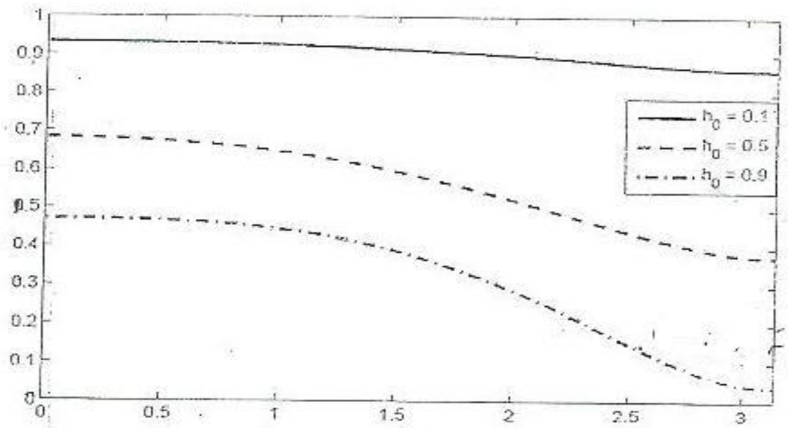

Figure 1: The normalized conductance changes of FFN system with increased angles between the magnetizations of two areas

The figure 2 shows the conductance behavior of FFS system by changing the angle between the magnetization vectors of two adjacent areas. It can be seen that the conductivity of FFS system relative to FFN system has almost double value in anti-parallel state of magnetization vectors. Also, a conductance maximum occurs for each value of the energy exchange at an angle other than θ = 0.Creating non-diagonal terms in superconductor's gap block in BdG equation through applying Hamiltonian of Bogoliubov De Zhan equation, the triplet spin states in the superconductor, and thus, Cooper pairs with spin triplet state will be created. Therefore, the Andreev reflection allows the reflection of holes with the same spin state of electrons to be emitted on the surface of superconductor. This will offset some of the decreasing effect of ferromagnetic on conductance of discussed connection.

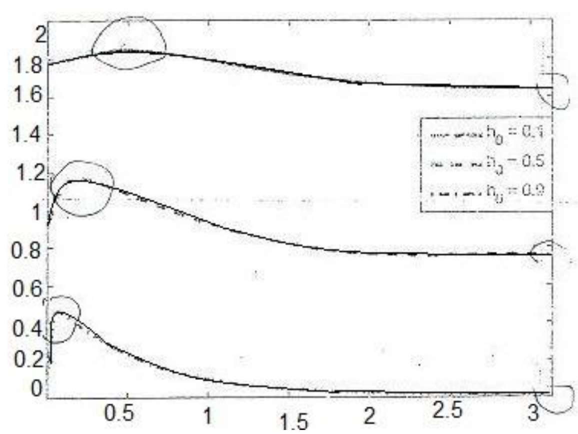

Figure 2: The dependency of FFS connection conductance on the angle between the magnetization vectors of two adjacent areas

Research Article

Conclusion

Using the scattering matrix method and Landauer-Büttiker equation for the conductance, the conductance dependency of two FFN, FFS connections on the angle between the magnetization vectors in two adjacent areas has been studied. It can be seen that the conductivity of FFS system relative to FFN system has almost double value in anti-parallel state of magnetization vectors. Also, a conductance maximum occurs for each value of the energy exchange in FFS system at an angle other than $\theta = 0$.

REFERENCES

De Jang MM and Seenekker OW (1995). *Journal of Physical Review Letter* **74** 1667.

Kashisaz Hadi and Zare'ian (No Date). The dependency of a connection conductance including ferromagnetic domain wall and a superconductor on the angle between the magnetizations in adjacent areas. *Application of Nanotechnology and Industrial Development Conference, 2010, Qazvin, Iran.*

Klapwijk TM *et al.*, (1999). *Nature* **397**(43).

Maleki M and Zareyan M (2006). *Physical Review B* **74** 144-512.

Shomali Z, Zareyan M and Belzig W (2008). *Physical Review B* **78** 214-518.

Zutic L *et al.*, (2004). Spintronics, Physics and Applications. *Review of Modern Physics* **76** 323- 410.