JOSEPHSON CURRENT IN d-WAVE SUPERCNDUCTOR JUNCTIONS WITH INHOMOGENEOUS FERROMAGNET

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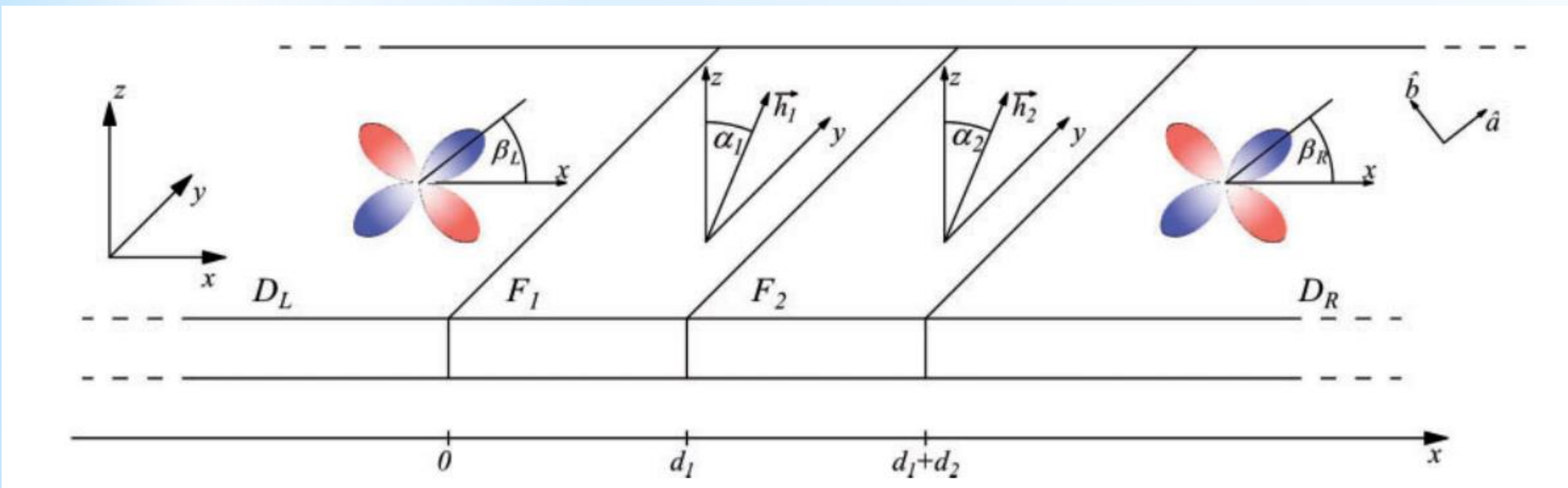
We study Josephson effect in a junction with arbitrarily oriented d-wave superconducting electrodes connected through two ferromagnets with noncollinear magnetizations. We solve the scattering problem based on the Bogoliubov-de Gennes formalism, extended to the case of anisotropic superconductors and presence of spin flip scattering due to ferromagnet interlayer. We investigate mutual influence of crystal orientation of superconducting electrodes and angle α between magnetizations in ferromagnetic bilayer of thickness d by calculating critical value of Josephson current I_C. For various orientation of superconducting electrodes, we calculate (d,α) phase diagram, and discuss the possibility to achieve except coexistence of two stable states 0 and π, also coexistence of three stable states 0, π and π/2, by varying the angle between magnetizations which can be much better for application compared to varying thickness of barrier or temperature. In the crossover point triply degenerate 0, π/2 and π equilibrium states occur, the fourth harmonic have dominant contribution and $I \sim \sin 4\varphi$, in the same way as in SFS junction where second harmonic have dominant contribution in 0-π crossover point. We observe also areas of coexistence of stable and metastable states.

DFFD JUNCTION



MODEL AND FORMALISM

Exchange fields in F_1 and F_2: $\mathbf{h_1}=h_1(0,\sin\alpha_1,\cos\alpha_1)$, $\mathbf{h_2}=h_2(0,\sin\alpha_2,\cos\alpha_2)$

$$\alpha = \alpha_2 - \alpha_1$$

Spatial variation of the pair potential:

$$\Delta(\mathbf{r},\theta)=\Delta_L(\theta)e^{-i\varphi_L}\Theta(-x)+\Delta_R(\theta)e^{-i\varphi_R}\Theta(x-d_1-d_2)$$

$$\Delta_L(\theta_\pm)=\Delta(T)\cos(2\theta\mp 2\beta_L) \qquad \Delta_R(\theta_\pm)=\Delta(T)\cos(2\theta\mp 2\beta_R) \qquad \theta_+=\theta, \qquad \theta_-=\pi-\theta$$

Temperature dependence of the order parameter: $\Delta(T)=\Delta(0)\tanh(1.74\sqrt{T_c/T-1})$

BOGOLIUBOV-de GENNES EQUATIONS

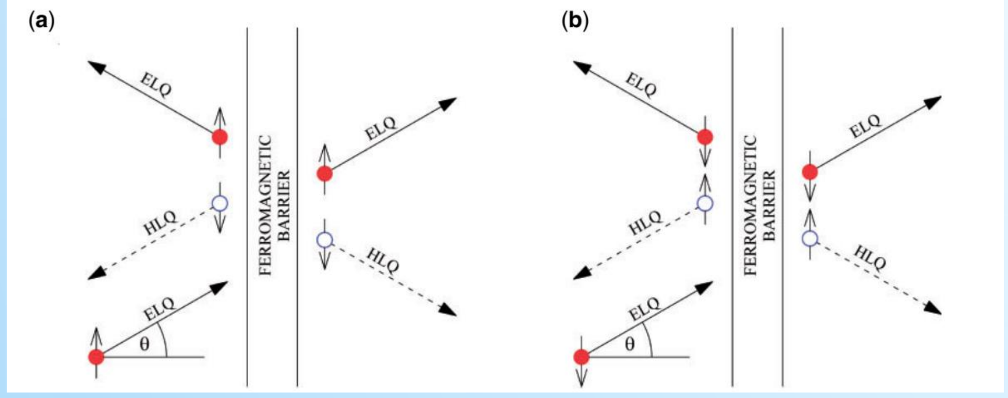
$$\begin{pmatrix} H_0-h_z & -h_x+ih_y & 0 & \Delta(\mathbf{r},\theta) \\ -h_x-ih_y & H_0+h_z & \Delta(\mathbf{r},\theta) & 0 \\ 0 & \Delta^*(\mathbf{r},\theta) & -H_0+h_z & -h_x-ih_y \\ \Delta^*(\mathbf{r},\theta) & 0 & -h_x+ih_y & -H_0-h_z \end{pmatrix}\begin{pmatrix} u_\uparrow(\mathbf{r},\theta) \\ u_\downarrow(\mathbf{r},\theta) \\ v_\uparrow(\mathbf{r},\theta) \\ v_\downarrow(\mathbf{r},\theta) \end{pmatrix}=E\begin{pmatrix} u_\uparrow(\mathbf{r},\theta) \\ u_\downarrow(\mathbf{r},\theta) \\ v_\uparrow(\mathbf{r},\theta) \\ v_\downarrow(\mathbf{r},\theta) \end{pmatrix}$$

Boundary conditions

$$\psi(x,\theta)|_{x_i+0,\theta}=\psi(x,\theta)|_{x_i-0}=\psi(x_i,\theta),$$
$$\frac{d\psi(x,\theta)}{dx}\Big|_{x_i+0}-\frac{d\psi(x,\theta)}{dx}\Big|_{x_i-0}=Z_i k_F^{(S)}\psi(x_i,\theta),$$

$$Z_i=2mW_i/\hbar^2 k_F^S$$

Schematic illustration of reflection and transmission at the ferromagnetic barrier of ELQ injected from the left superconductor for spin up (↑) and spin down (↓) projection



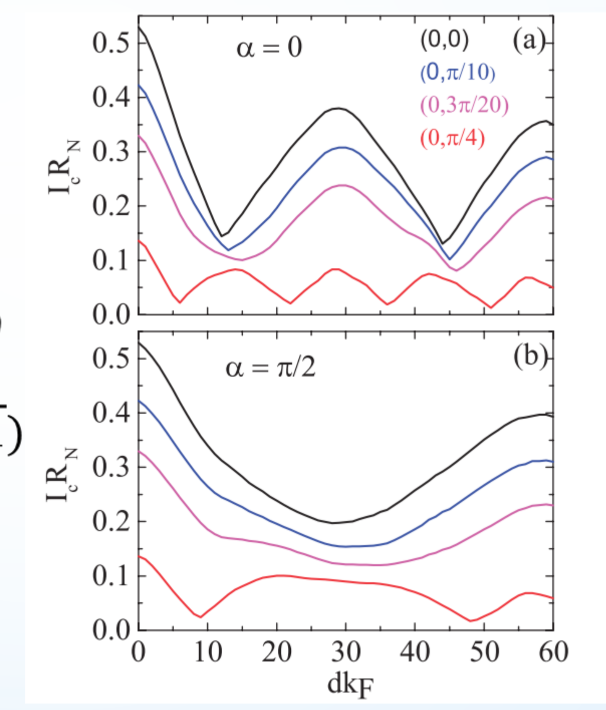
JOSEPHSON CURRENT

$$I(\varphi)=-\frac{ek_BT}{2\hbar}\sum_{\omega_n}\sum_{\sigma}\sum_{k_y}\left(\frac{a_{n\sigma}}{2\Omega_{L+n}}|\Delta_L(\theta_+)|\frac{k_{L-n}+k_{L+n}}{k_{Fx}}\right.$$
$$\left.-\frac{\tilde{a}_{n\sigma}}{2\Omega_{L-n}}|\Delta_L(\theta_-)|\frac{\tilde{k}_{L-n}+\tilde{k}_{L+n}}{k_{Fx}}\right).$$

$$I_c=max_\varphi|I(\varphi)|$$

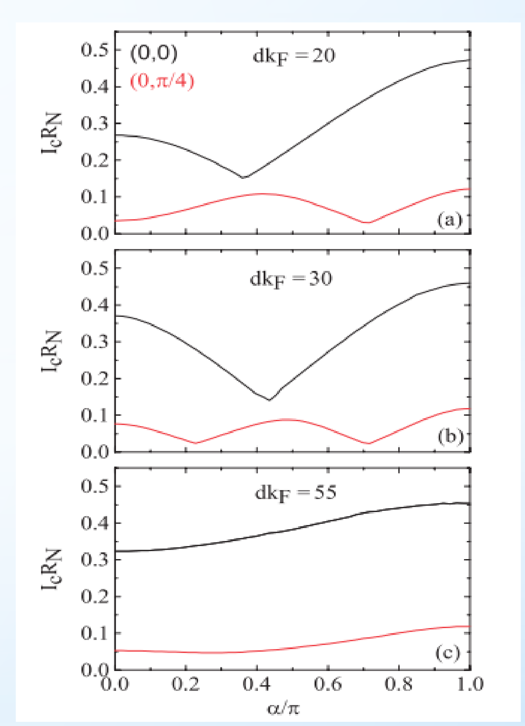
The critical current I_c as a function of:

ferromagnetic interlayer thickness d



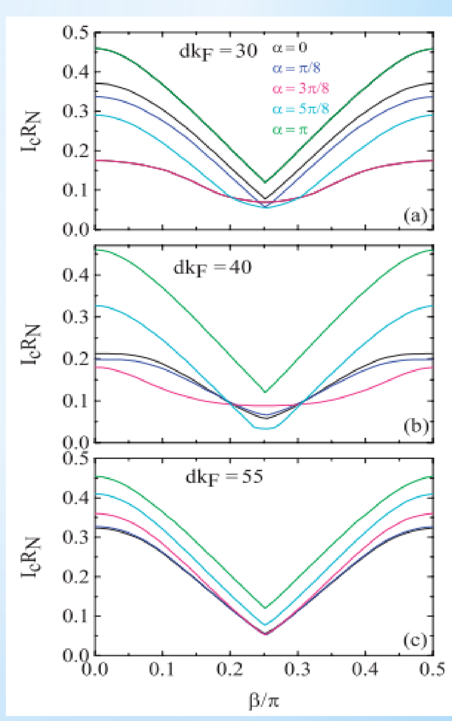
In $(0,\pi/4)$ type of junction there is another transport channel for supercurrent resulting in that the Josephson current has twice the periodicity in phase compared to the case of a conventional or d-wave junction with $\beta_R \neq \pi/4$.

the misorientation angle α



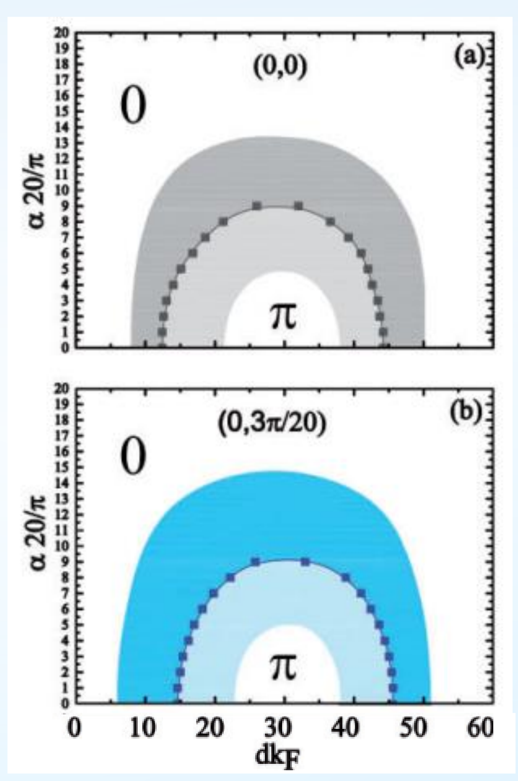
Fine-tuning between 0 and π states in (0,0) types of junction, and $\pi/2$, 0 and π states in $(0,\pi/4)$ types of junction, could be more esily achieved by changing relative angle between the in-plane magnetization α instead of the thickness.

d-wave superc. crystal orientation β



Two branches are observed on the curves that are symmetrical with respect to $\beta=\pi/4$ depending on the value of α and barrier thickness d. Sharp dip is connected with the $\pi/2$ state, which can be observed in $(0,\pi/4)$ type of junction, while a smooth minimum means that it is not possible to observe the $\pi/2$ state with that choice of parameters.

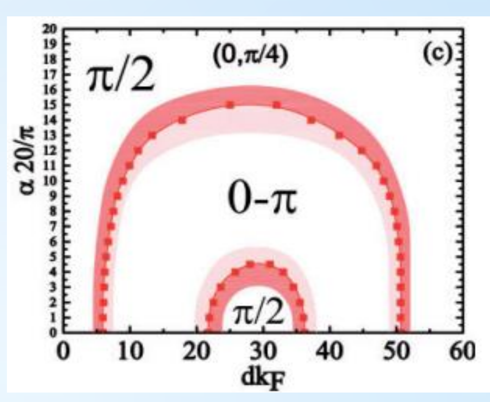
Phase diagram



The line formed by a large scatters separates the parameter areas for which the junction is in a 0 or a π stable states. For the value of parameters from the line scatter there are the coexistence of stable 0 and π states. Shaded zones around semicircles present the area of parameters where stable and metastable states can coexist.

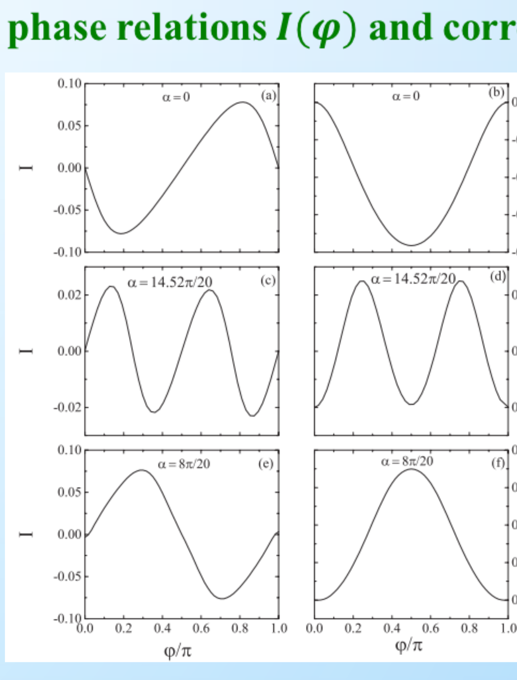
$T/T_c = 0.1$

$h/E_F = 0.1$



For a values of parameters from two scatter lines there are triplets of stable states $0, \pi/2$ and π.

Current phase relations $I(\varphi)$ and corresponding free energy $W(\varphi)$



$\alpha = 0$
the only stable state is $\varphi=\pi/2$
$I(\varphi)\sim\sin(2\varphi+\pi)$

$\alpha = 14.52\pi/20$
triplets of stable states $\varphi=0,\pi/2,\pi$
$I(\varphi)\sim\sin(4\varphi)$

$\alpha = 8\pi/20$
coexistence of stable s $\varphi=0$ and π
$I(\varphi)\sim\sin(2\varphi)$

REFERENCES

S. Djurdjević and Z. Popović, Progres of Theoretical and Experimental Physics **2021**, 083I02 (2021).