# Сверхпроводящий триплетный спиновый клапан: теория и эксперимент

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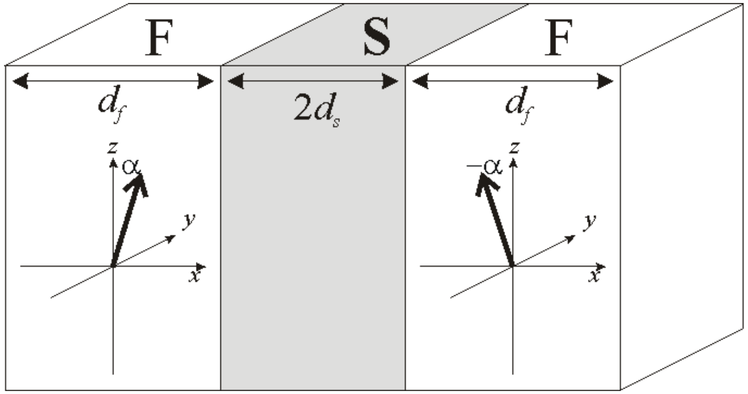
[1] Ya.V. Fominov, A.A. Golubov, T.Yu. Karminskaya, M.Yu. Kupriyanov, R.G. Deminov, L.R. Tagirov, *Письма в ЖЭТФ* **91**, 329 (2010) [*JETP Lett.* **91**, 308 (2010)]

[2] P.V. Leksin, N.N. Garif'yanov, I.A. Garifullin, Ya.V. Fominov, J. Schumann, Y. Krupskaya, V. Kataev, O.G. Schmidt, B. Büchner, *Phys. Rev. Lett.* **109**, 057005 (2012)

[3] P.V. Leksin, A.A. Kamashev, N.N. Garif'yanov, I.A. Garifullin, Ya.V. Fominov, J. Schumann, C. Hess, V. Kataev, B. Büchner, *Письма в ЖЭТФ* **97**, 549 (2013)

# Introduction




Theory:

- $T_c^{\mathrm{P}} < T_c^{\mathrm{AP}}$ (compensation of exchange fields at AP orientation), hence the standard switching effect: $\Delta T_c = T_c^{\mathrm{AP}} - T_c^{\mathrm{P}} > 0$
  - superconducting spin valve [Tagirov (1999); Buzdin, Vedyayev, Ryzhanova (1999)]

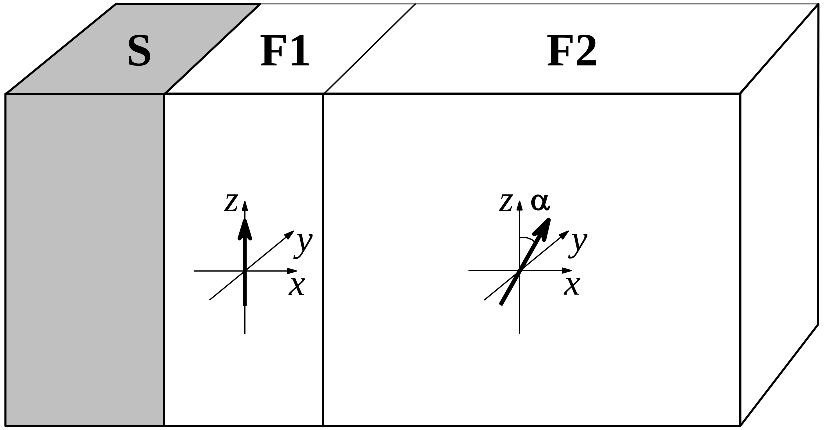
- Long-range triplet superconducting correlations at noncollinear orientations ( $k_h = \sqrt{h/D} \gg k_\omega = \sqrt{2\omega/D}$ – short- and long-range wave vectors) [Bergetet, Volkov, Efetov (2001)]

- $T_c(\alpha)$ at all $\alpha$; monotonic [Fominov, Golubov, Kupriyanov (2003)]

Experiment:

- From $\Delta T_c \approx 3$ mK [Gu *et al.* (2002)] to maximal $\Delta T_c \approx 41$ mK [Moraru, Pratt, Birge (2006)]
- Sometimes $\Delta T_c < 0$ – inverse switching effect

# Motivation




Theory:

No qualitative differences from FSF

[Oh, Youm, Beasley (1997)]

Experiment:

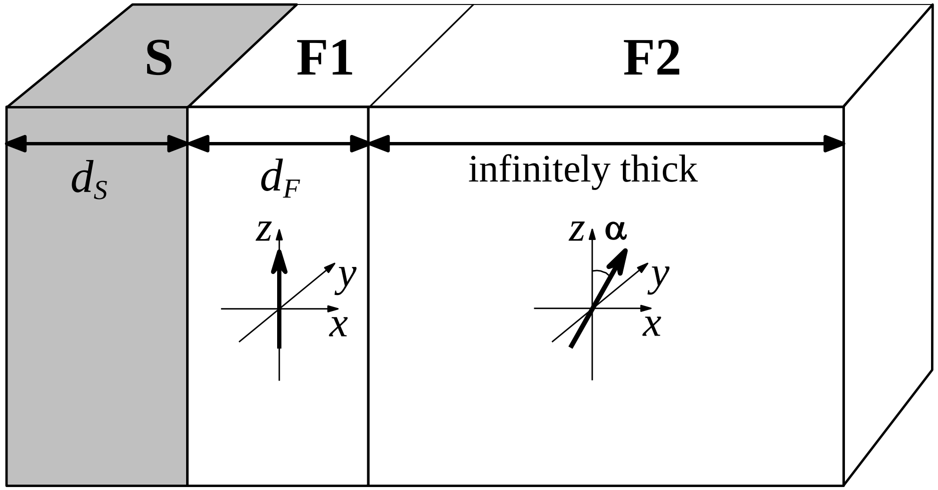
Maximal $\Delta T_c(\alpha) \approx 200$ mK [Nowak *et al.* (2008)]

– much larger than in FSF

Questions:

- May be some new physics?
- Shielding effect of the middle layer at $k_h^{-1} \ll d_{F1} \ll k_\omega^{-1}$ ?
- Nonmonotonic $T_c(\alpha)$ ?

# Formulation of the problem




- Ideal (transparent) interfaces
- Equal diffusion constants in all the layers
- Infinitely thick F2 layer
- $h << E_F$

# Equations

$$\frac{D}{2}\frac{d^2\check{f}}{dx^2} - |\omega|\check{f} - \frac{i\,\mathrm{sgn}\,\omega}{2}\{\hat{\tau}_0(\mathbf{h}\hat{\boldsymbol{\sigma}}),\check{f}\} + \Delta\hat{\tau}_1\hat{\sigma}_0 = 0$$

Characteristic wave vectors: $k_h = \sqrt{h/D}, \quad k_\omega = \sqrt{2\omega/D}$

$$\check{f} = \hat{\tau}_1\left(f_0\hat{\sigma}_0 + f_3\hat{\sigma}_3 + f_2\hat{\sigma}_2\right)$$

- 4×4 matrix in the Nambu-Gor’kov ⊗ spin spaces

$\hat{\tau}$ - Pauli matrices in the Nambu-Gor’kov space

$\hat{\sigma}$ - Pauli matrices in the spin space

Components, symmetries, and wave vectors in F:

| | | |
|---|---|---|
| $f_0(-\omega) = f_0(\omega),$ | $(1+i)k_h$ | - singlet |
| $f_3(-\omega) = -f_3(\omega),$ | $(1+i)k_h$ | - triplet with projection 0 |
| $f_2(-\omega) = -f_2(\omega),$ | $k_\omega$ | - triplet with projections ±1 |

# Reduced effective problem

All components are found explicitly, except for $f_0(x)$ in S
- this component is self-consistently "entangled" with $\Delta(x)$.

As a result, we obtain an effective problem for $f_0(x)$:

$$\Delta(x) \ln \frac{T_{cS}}{T_c} = 2\pi T_c \sum_{\omega>0} \left( \frac{\Delta(x)}{\omega} - f_0(x) \right)$$

$$\frac{D}{2} \frac{d^2 f_0}{dx^2} - \omega f_0 + \Delta = 0,$$

$$\left. \frac{df_0}{dx} = 0 \right|_{x=-d_S}, \qquad \left. -\xi \frac{df_0}{dx} = W f_0 \right|_{x=0}.$$

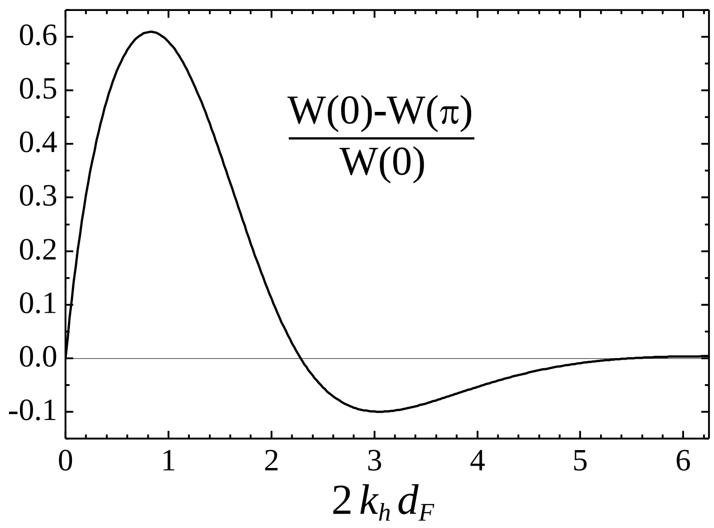
The larger $W$, the smaller $T_c$.

Then: analytics at $k_\omega << k_h$, numerics at arbitrary ratio.

# Standard and inverse switching

$$W(0) = 2k_h\xi$$

$$W(0) - W(\pi) = 2k_h\xi \frac{\sqrt{2}\sin(2k_h d_F + \pi/4) - e^{-2k_h d_F}}{\sinh(2k_h d_F) + \cos(2k_h d_F)}$$

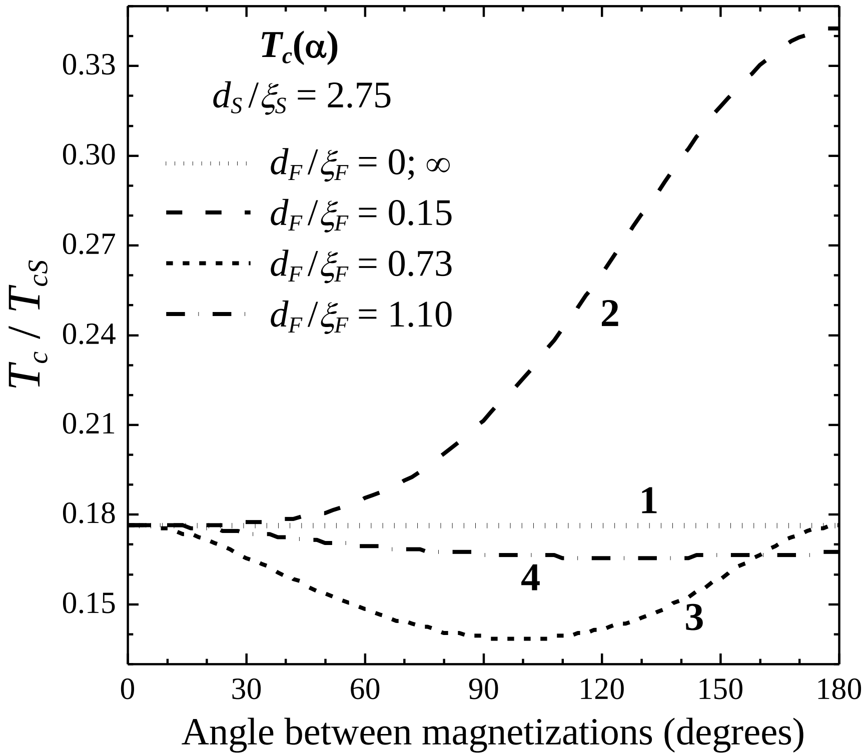


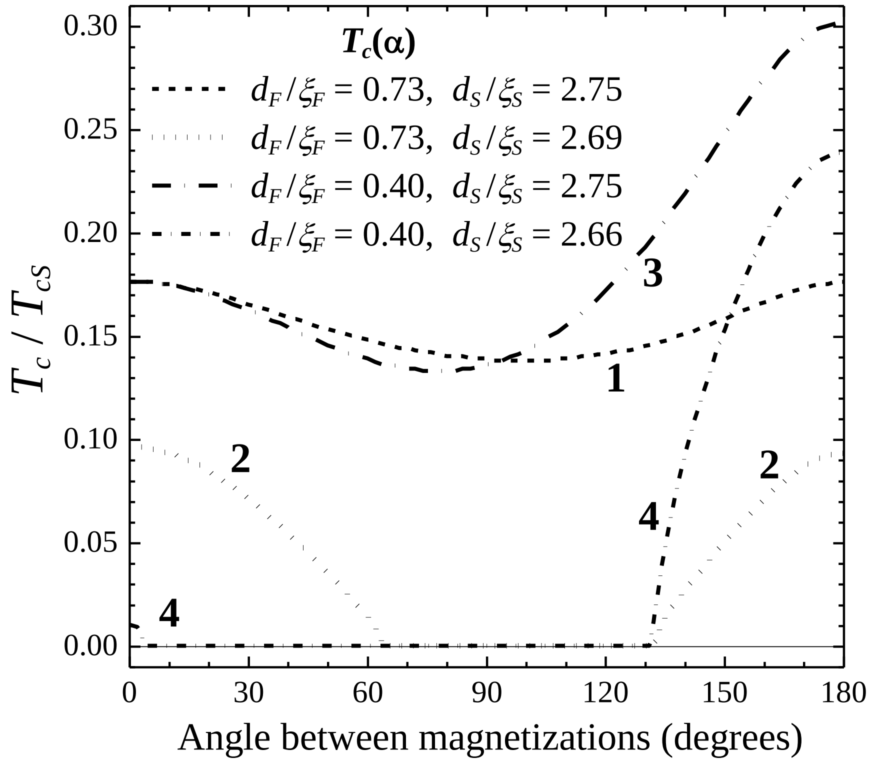

Fominov *et al.*, Письма в ЖЭТФ (2010)

Both the standard ($T_c^{\mathrm{P}} < T_c^{\mathrm{AP}}$) and inverse switching effects ($T_c^{\mathrm{P}} > T_c^{\mathrm{AP}}$) are possible due to quantum interference in the middle F layer (complex wave vector $(1+i)k_h$).

# Triplet spin valve

$W(\alpha)$ grows as $\alpha$ deviates from $0$ or $\pi$ (analytics at $k_\omega << k_h$), hence $T_c(\alpha)$ has a minimum at some noncollinear orientation.

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# Experimental results.
# 1. Hysteresis

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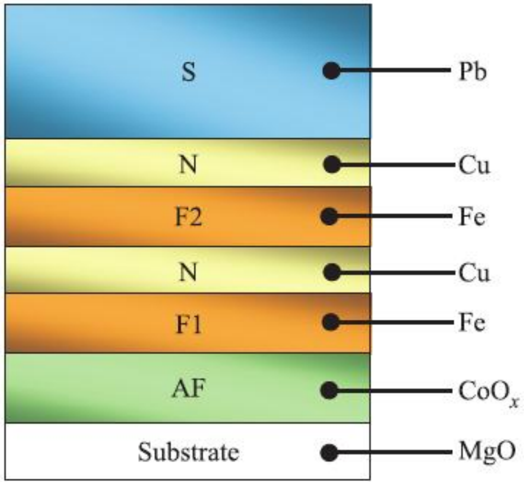


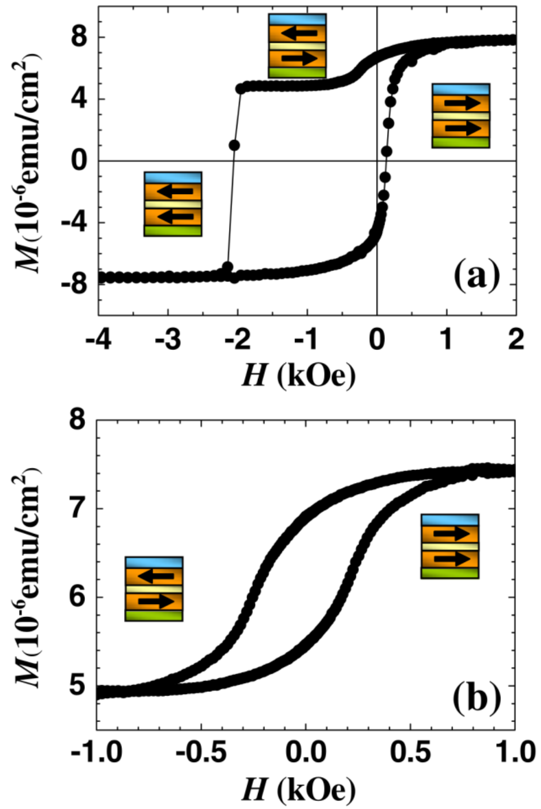


FIG. 1 (color online). (a) Major magnetic hysteresis loop for the CoO/Fe1/Cu/Fe2/Pb sample with $d_{Fe2} = 0.7$ nm cooled from room temperature down to $T = 4$ K in a magnetic field $H = 4$ kOe; (b) central part of the minor hysteresis loop for the same sample due to the reversal of the magnetization of the free Fe2 layer.

$CoO_x$(4 nm)/Fe(2.5 nm)/Cu(4 nm)/Fe($d_{Fe2}$)/Pb(35 nm)

# Experimental results.
# 2. Standard and inverse switching

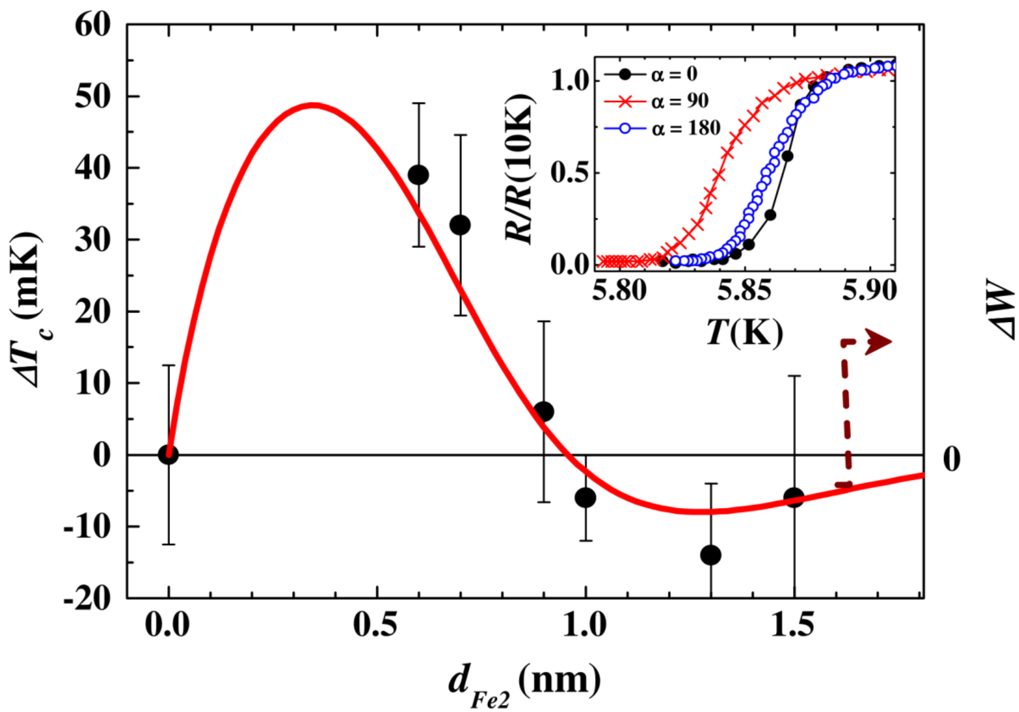


FIG. 2 (color online). Dependence of the magnitude of the spin valve effect $\Delta T_c$ on the thickness of the Fe2 layer at a fixed value of the $S$ layer $d_{\mathrm{Pb}} = 35$ nm. The solid line is a theoretical curve (see the text). The inset shows the SC transition curve for the sample with $d_{\mathrm{Fe2}} = 1.3$ nm at $H = 1$ kOe for three different angles between magnetizations of the Fe1 and Fe2 layers.

$$\frac{\Delta W}{W(0)} = \frac{\sqrt{2}\sin(2k_h d_F + \pi/4) - e^{-2k_h d_F}}{\sinh(2k_h d_F) + \cos(2k_h d_F)}$$

Leksin *et al.*, PRL (2012)

# Experimental results.
# 3. Triplet spin valve

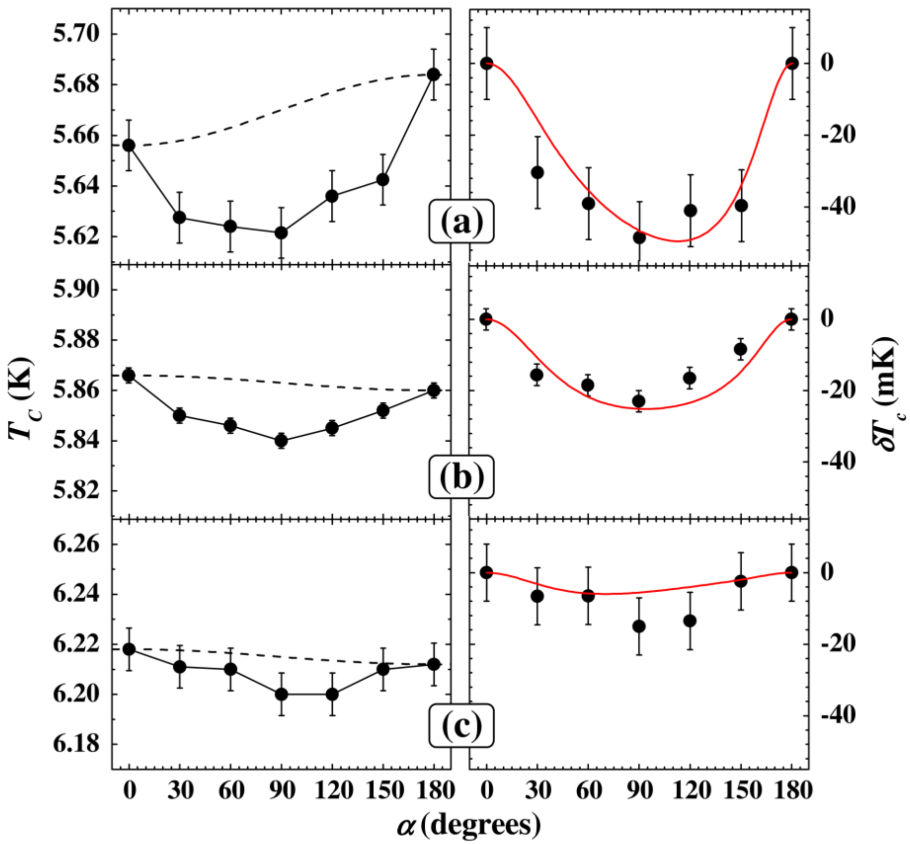


FIG. 3 (color online). Left: Dependence of $T_c$ on the angle between magnetizations of the Fe1 and Fe2 layers measured in a field $H = 1$ kOe for the samples with $d_{Fe2} = 0.6$ (a), 1.0 (b), and 1.5 nm (c). Dashed lines are the reference curves calculated according to Eq. (2). Right: Deviations $\delta T_c$ of the actual $T_c$ values from the respective reference curves. Solid lines are theoretical results for $\delta W$ (see the text).

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# Experimental results.
# 4. Triplet spin valve

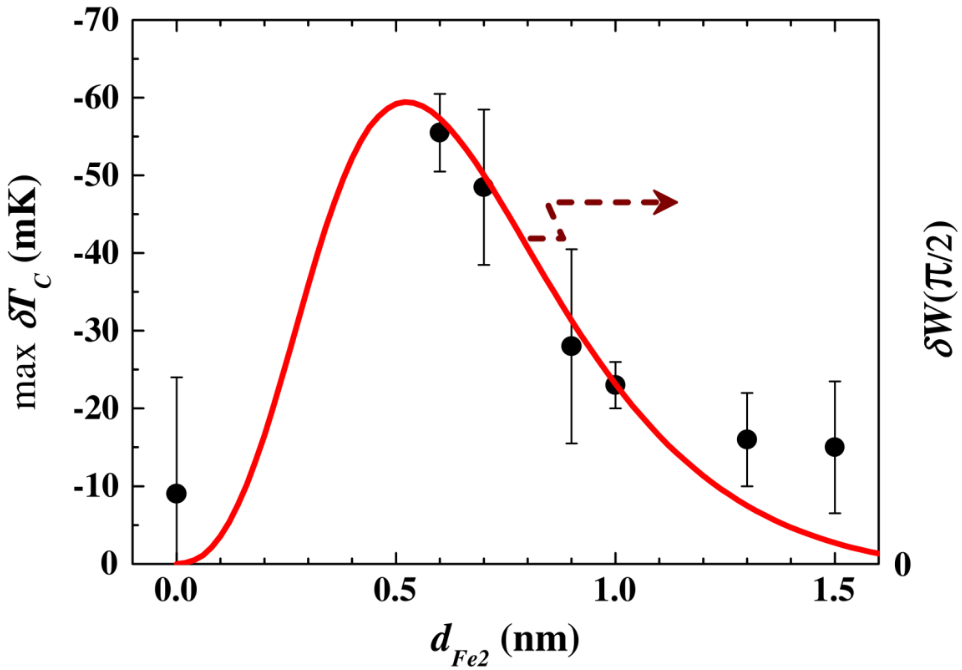


FIG. 4 (color online). Dependence of the maximal deviation of $T_c$, max$\delta T_c$, on the thickness of the Fe2 layer. The solid line is the theoretical result for $\delta W(\pi/2)$ according to Eq. (3) (see the text).

$$\frac{\delta W(\pi/2)}{W(0)} = -\frac{\sqrt{2}\sin(2k_h d_{\mathrm{Fe2}} + \pi/4) - e^{-2k_h d_{\mathrm{Fe2}}}}{2\left[\sinh(2k_h d_{\mathrm{Fe2}}) + \cos(2k_h d_{\mathrm{Fe2}})\right]} - \frac{4\left[\sin^2(k_h d_{\mathrm{Fe2}}) - 2k_\omega d_{\mathrm{Fe2}}\right]}{e^{2k_h d_{\mathrm{Fe2}}} - 2 + \sqrt{2}\cos(2k_h d_{\mathrm{Fe2}} + \pi/4) + 4k_\omega/k_h}$$

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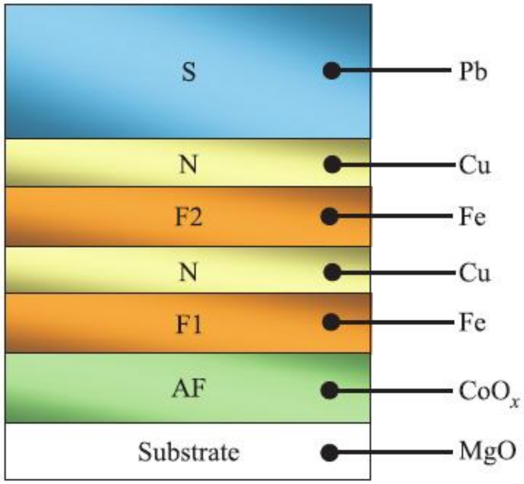
# Experimental results, finite $d_{Fe1}$. 1. Switching effect



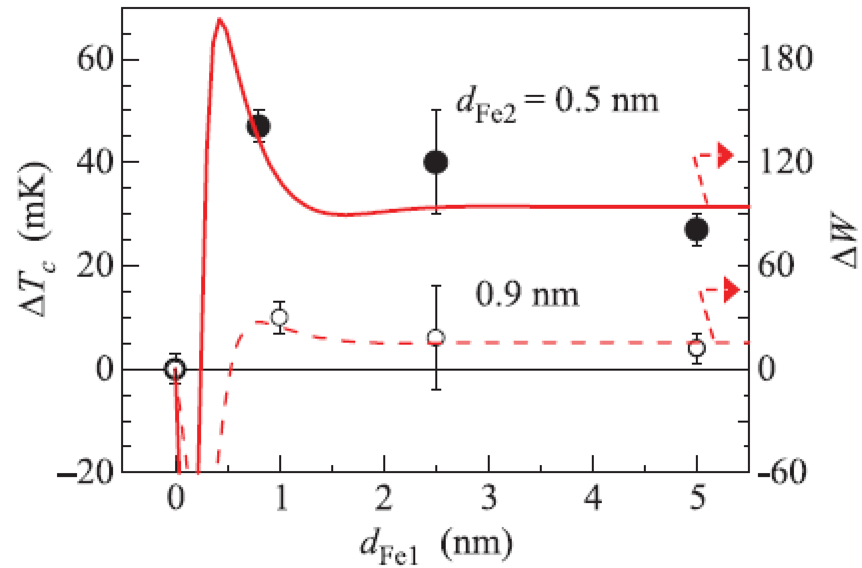




Fig. 3. The dependence of the $T_c$ shift $\Delta T_c = T_c^{AP} - T_c^{P}$ on the Fe1 layer thickness $d_{Fe1}$ for the series of the samples with $d_{Fe2} = 0.5$ nm (•) and 0.9 nm (○) at fixed $d_{Pb} = 35$ nm. The applied switching field $H_0 = \pm 1$ kOe lies in the plane of the film. Solid and dashed lines are theoretical curves for $\Delta W$ (see the text)

$$\frac{\Delta W}{2k_h\xi} = \frac{\sigma_F}{\sigma_S}\left(\frac{\cosh(d_1+d_2) - \cos(d_1+d_2)}{\sinh(d_1+d_2) - \sin(d_1+d_2) + 2\kappa\tanh(k_\omega d_S)} - \frac{\mathcal{N}}{\mathcal{D}}\right)$$

$$\mathcal{N} = \cosh d_1 \cosh d_2 - \cos d_1 \cos d_2 - \sin d_1 \sinh d_2 - \sinh d_1 \sin d_2$$

$$\mathcal{D} = \cosh d_1 \sinh d_2 + \sinh d_1 \cos d_2 - \sin d_1 \cosh d_2 - \cos d_1 \sin d_2 + 2\kappa\tanh(k_\omega d_S)$$

$$d_1 = 2k_h d_{Fe1}, \quad d_2 = 2k_h d_{Fe2}, \quad \kappa = \frac{\sigma_S k_\omega}{\sigma_F k_h}$$

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# Experimental results, finite $d_{Fe1}$. 2. Transition curves

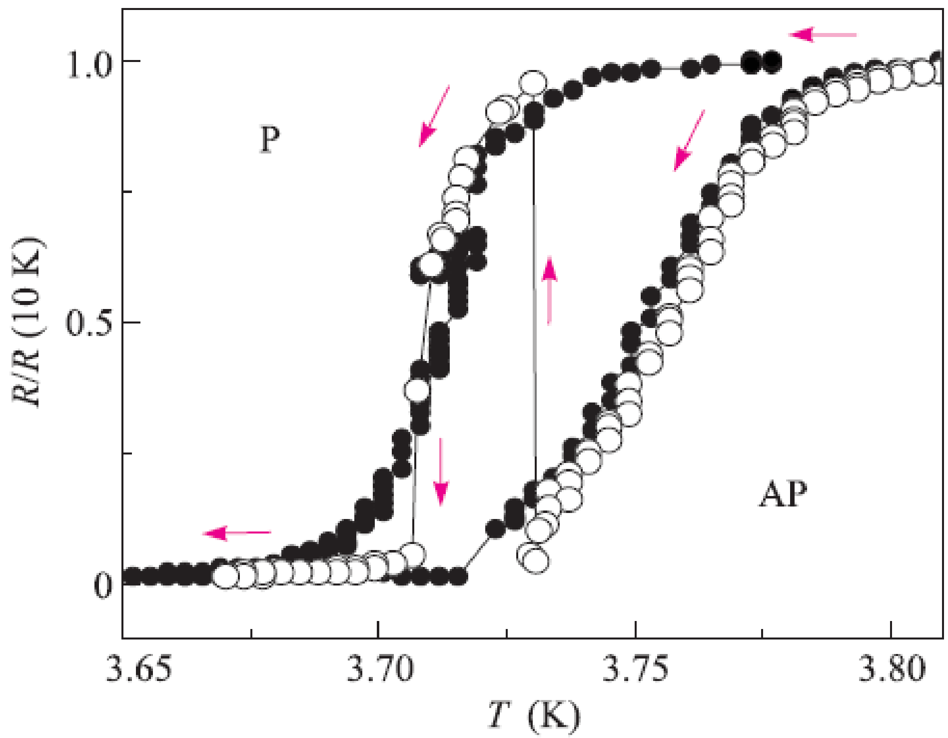


Fig. 4. Superconducting transition curves for P ($H_0 = +1$ kOe) and AP ($H_0 = -1$ kOe) orientations of the Fe1 and Fe2 layers' magnetizations, respectively, for the sample $CoO_x$/Fe1(0.8 nm)/Cu(4 nm)/Fe2(0.5 nm)/Cu(1.2 nm)/Pb(60 nm) (•). Instant switching between superconducting state and normal state by switching between AP ($H_0 = -1$ kOe) and P ($H_0 = +1$ kOe) orientations of the Fe1 and Fe2 layers' magnetizations during a slow temperature sweep (○)

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