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# Nucleation of superconducting domains in thin s-layers of S-F/N-sIS Josephson devices.

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## Introduction

Josephson junctions containing normal (N) and ferromagnetic (F) materials in the weak link region are currently the subject of intense research. The interest in such structures is due to the possibility of their use as a control elements of superconductor memory compatible with the RSFQ logic. At present there are many implementations of such controls. Among them, the tunnel structures containing single ferromagnetic layer in the weak link region, are of greatest interest. Anisotropy of their properties necessary for operation of the cell is achieved in such devices by complicating the structure of the weak-coupling area.

In this work we describe effect of nucleation of phase domains in superconductive film. They are induced by proximity with bulk electrodes through ferromagnetic and normal layers. We also consider possible applications of this phenomenon and propose some devices: Josephson key and memory element.

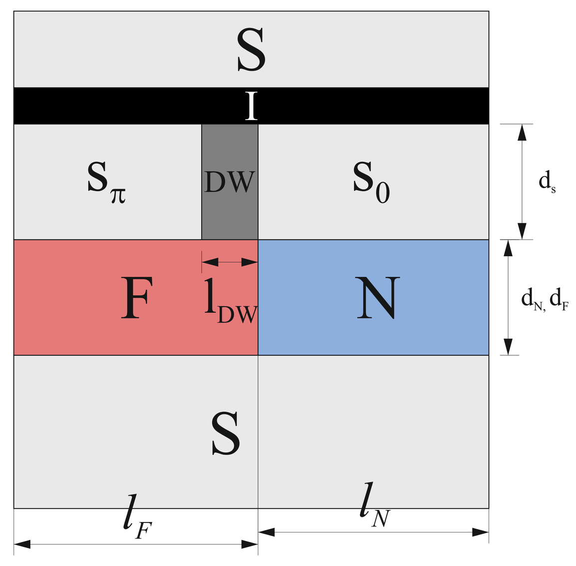
## Basics

### *Numerical Solution*

***2D Boundary Problem:***
*Usadel Equations*
*KL boundary condtitions*
*Self-consitent solution*

***We assume:***

- *Dirty limit in materials*
- *Neglect suppression in S electrodes*
- *Structure is much smaller than Josephson penetration depth $l_{FN} << \lambda_J$*




### *Analitical Estimates*

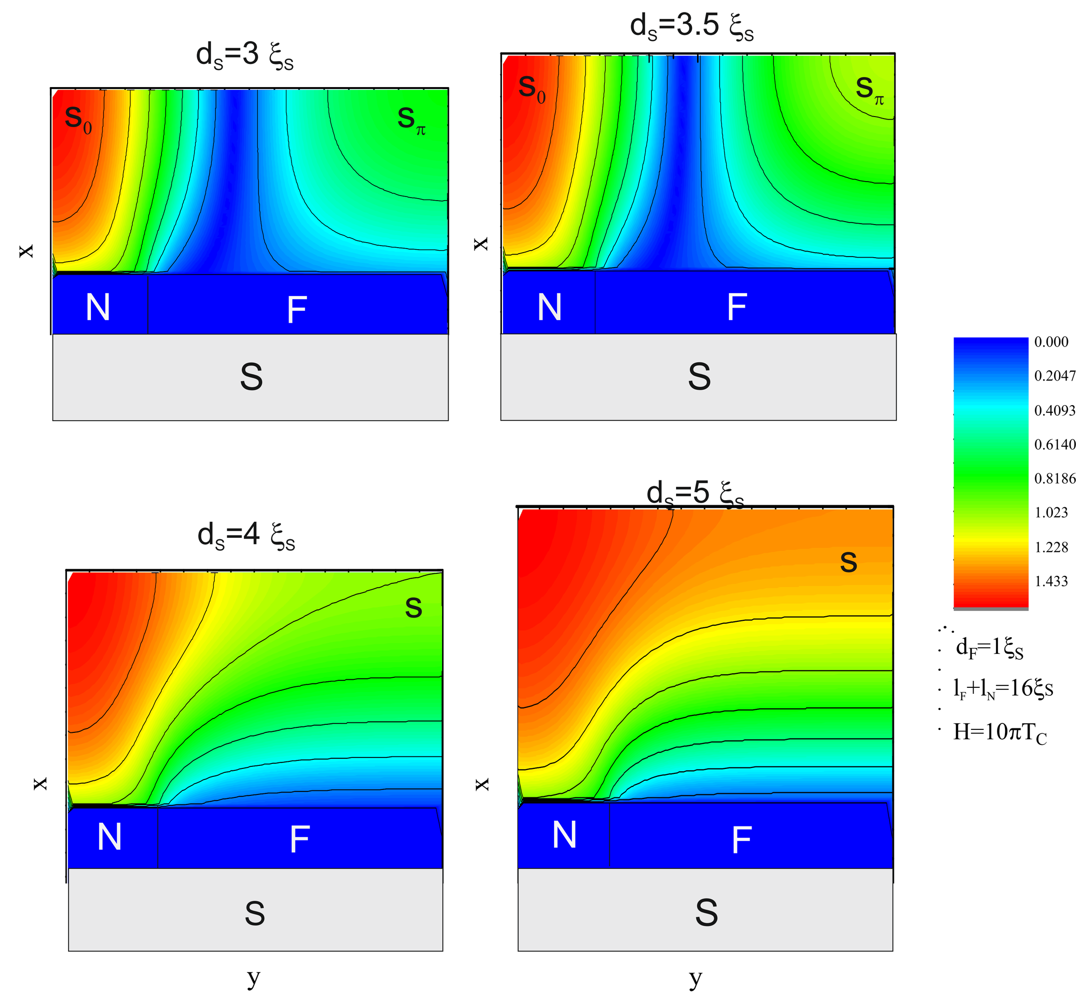
The problem is reduced to comparison of three energies:

- Josephson Energy of SFs junction $\Delta E_{SFs}$
- Josephson Energy of SNs junction $\Delta E_{SNs}$
- Pairing Energy of domain wall volume $\Delta E_{DW}$

$$\Delta E_{DW} = \Delta F_{GL} l_{DW} d_s W + \frac{\hbar j_{Cs} d_s W}{e} \sim d_s$$
$$\Delta E_{SFs} = \frac{\hbar j_{CF} l_F W}{e} \sim l_F$$
$$\Delta E_{SNs} = \frac{\hbar j_{CN} l_N W}{e} \sim l_N$$

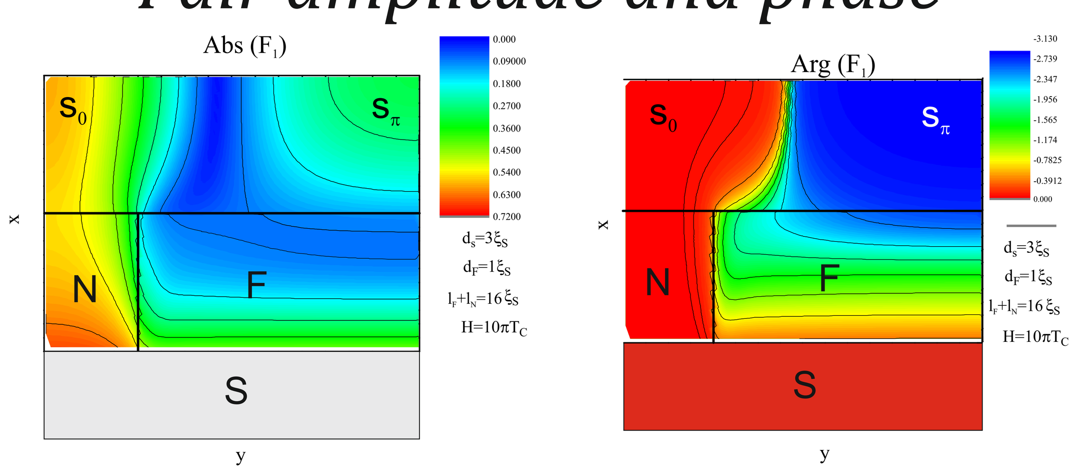
## S - Domains

### *Pair Potential Δ*



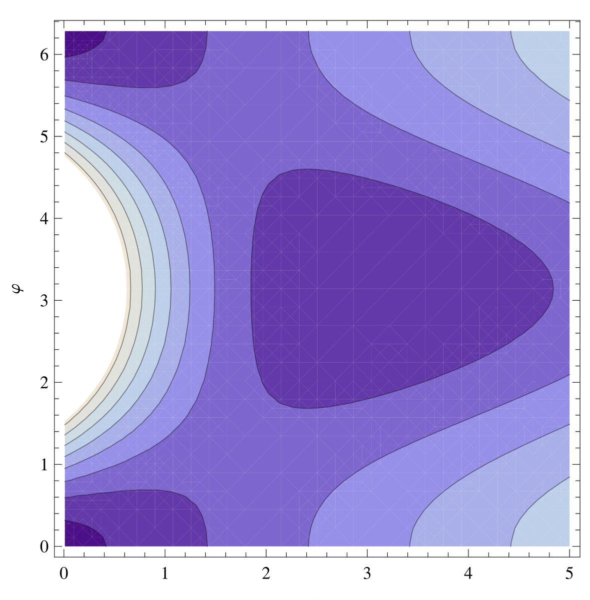

Spatial distribution of pair potential Δ in the middle part of S-N/F-s structure for different thickness of the thin s-layer $d_s$. While s film is larger than critical value ($d_s$ = 4 and $d_s$ = 5), the single domain exists. The suppression of pair potential is differs in the vicinities of boundaries with F and N layers, but with equal phase in the whole s-layer.
Thin s films ($d_s$ = 3 and $d_s$ =3. 5) are separated into two domains $s_0$ and $s_\pi$, divided each other by area of suppressed superconductivity named "domain wall".

### *Pair amplitude and phase*




Spatial distribution of the amplitude (left) and phase (right) of Anomalous Green function $F_1$ at the first Matsubara frequency in the middle part of S-N/F-s structure for separated on domains state. Proximity effect from bottom electrode provides finite pair amplitude in the N and F layers. The rotation of phase in the F layer leads to formation of domain with phase π in the superconductive s-film.

## Memory




Energy of the system in the critical state between separated on domains and unseparated states thin s-film versus the phase of $s_\pi$-domain φ and thickness of the domain wall $l_{DW}$. Dark part are the minima and bright parts are the maxima of energy.

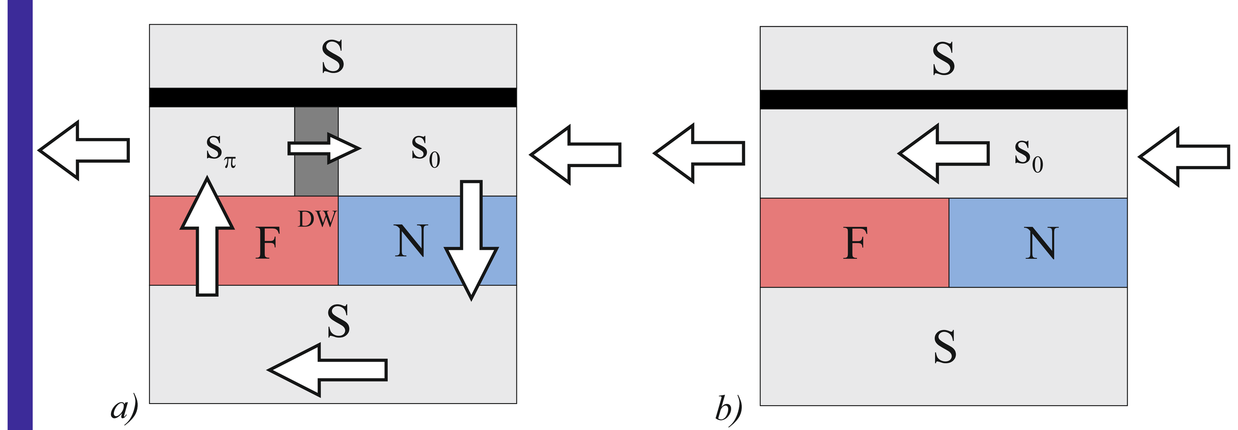
$$E = \frac{\hbar J_{Cs}(l_{DW})}{2e}(1-\cos\varphi) + \frac{\hbar J_{CSFs}}{2e}(1-\cos(\pi-\varphi)) + \Delta E_{DW}(l_{DW})$$

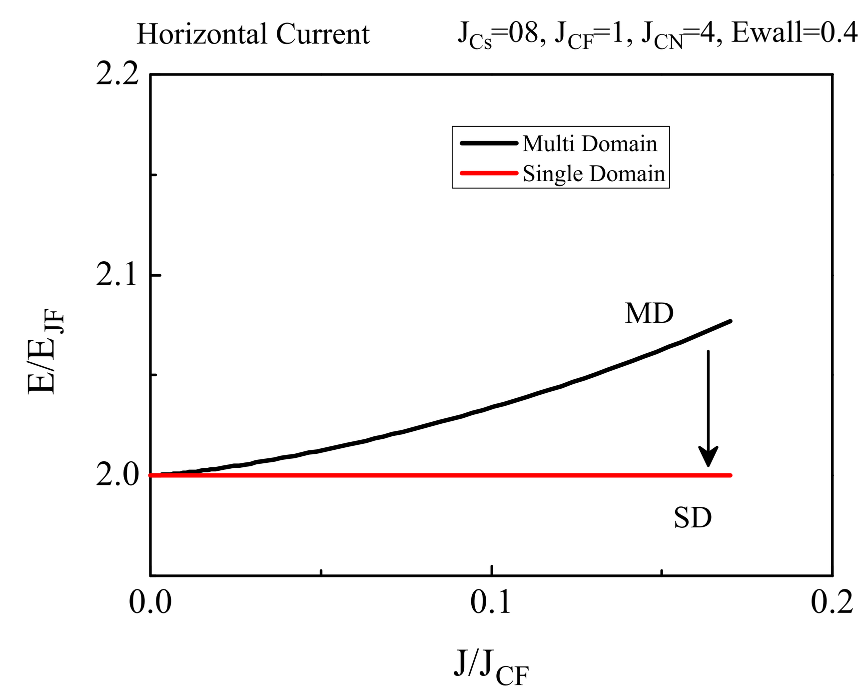
There are two local minima of energy. The first one is in the left corner at the zero phase of $s_\pi$-domain and disappearance of domain wall ($l_{DW}$=0) is related to unseparated state. The other minimum exists with finite thickness of domain wall ($l_{DW}$=3) and phase (φ=π). It corresponds to formation of domains described above.

The local minima are connected through energy wall, which protects the system from spontaneous switching between the states. Also this energy value determines required value of injected current to manual switch of the system. Furthermore, system conserves its final state after disappearance of the current due to this energy wall. Thus S -F/N-sIS junctions can be applied as memory element.

## Josephson Key Device

### *Switching: Horizontal Current*

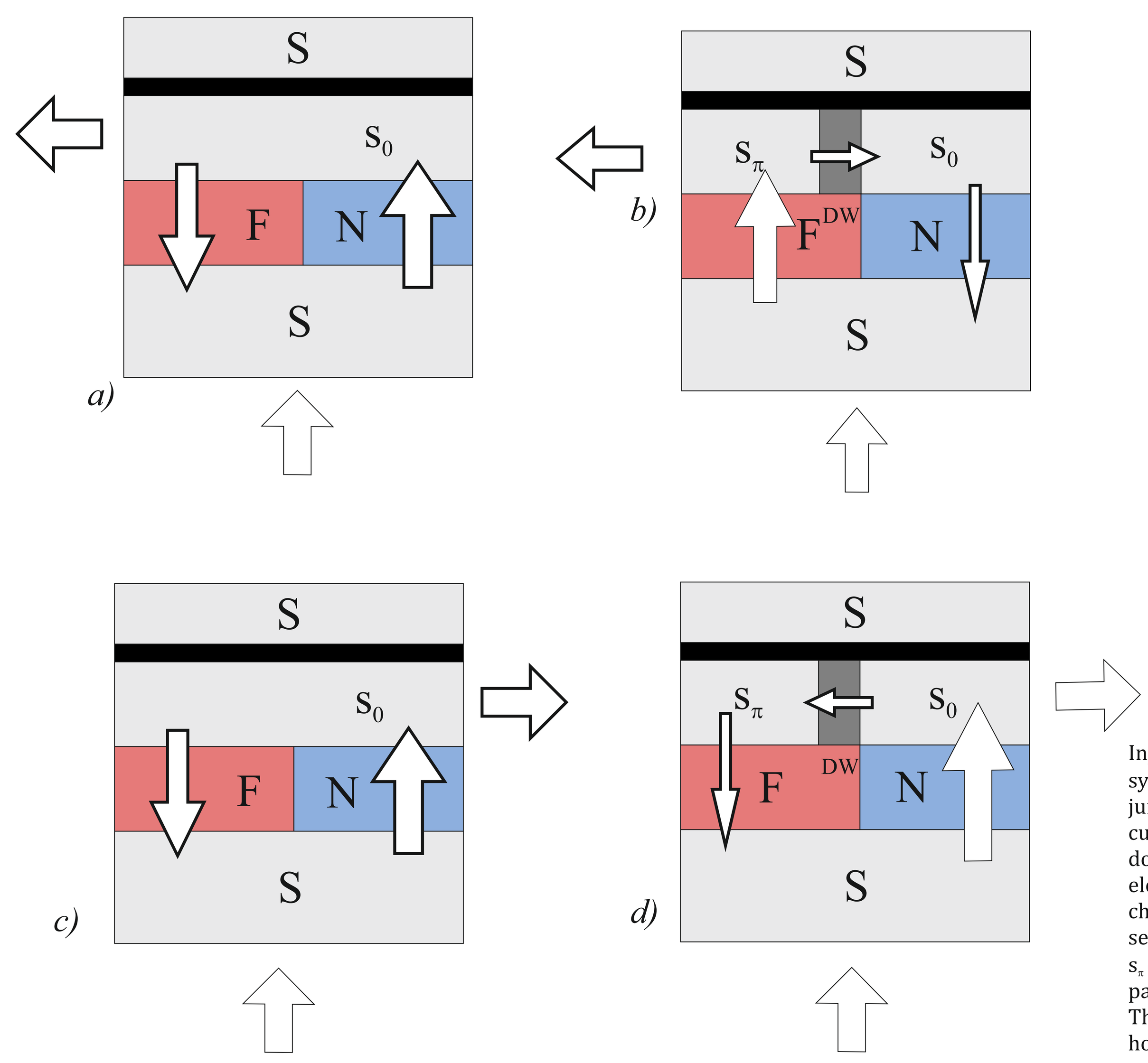


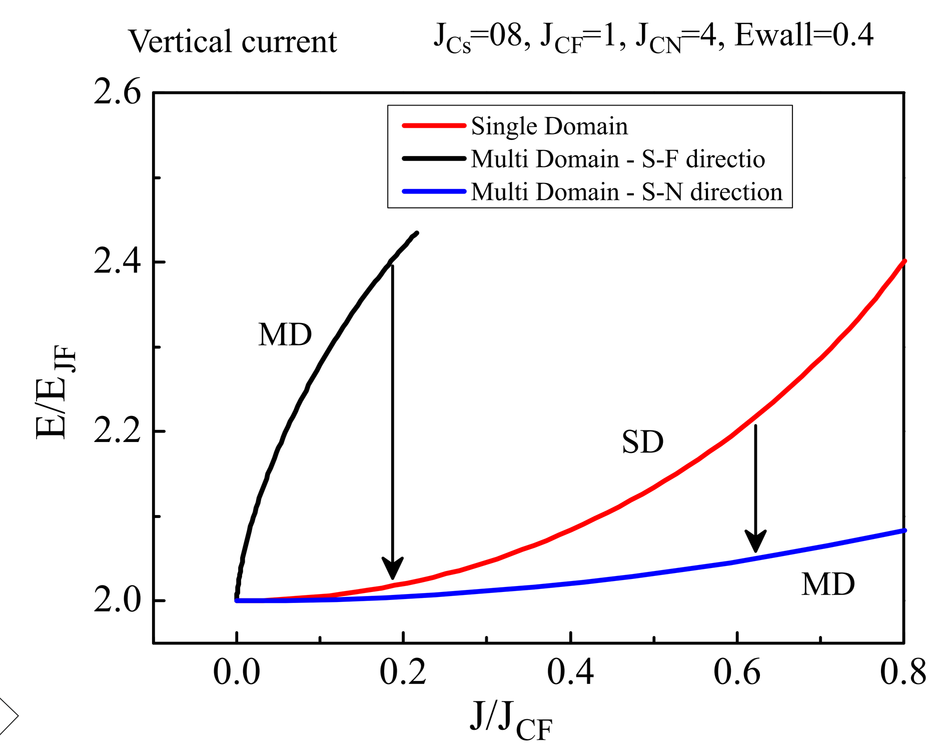




The system state can be switched by external current. Current distribution is different for system with or without domain wall, which can be modeled as additional Josephson junction inside the system. In the unseparated s-film, current goes directly through it and change of the energy is neglectable, because this current is much smaller than depairing one. In the opposite case, current through s-film is blocked by domain wall with relatively small critical current, and the main channel of current flowing is bottom N-S-F path. Moreover, sp domain has initial phase difference with $s_0$ domain, and current between them is negative.

Thus this current distribution provides different energy increment with growth of the current for the single and multi domain states. It results in disappearance of domain wall and switching of the system in single domain state.

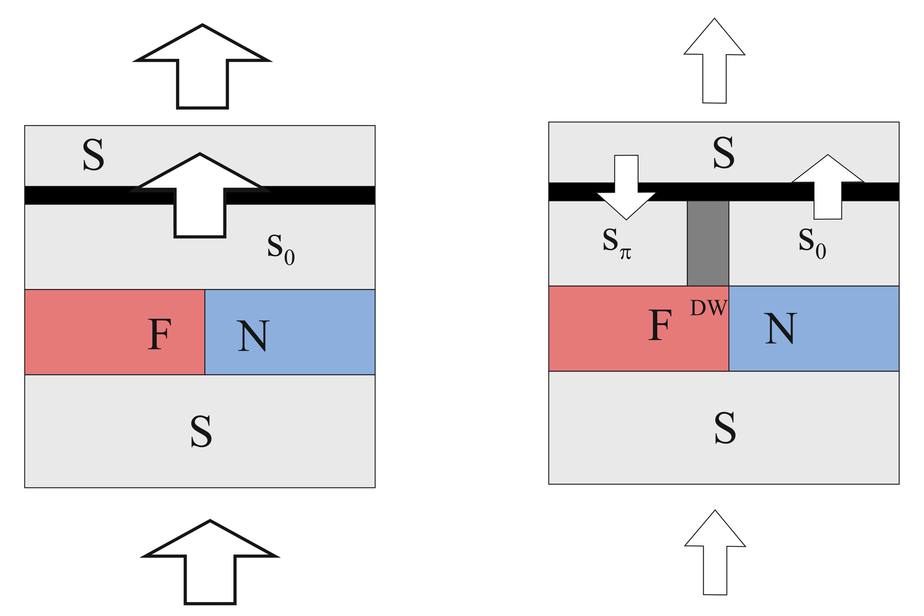
### *Switching: Vertical Current*




Injection of current through bottom S electrode provides other possibilities to switching of the system. In the case of unseparated s-film, system operates like conventional double channel 0/π junction: the currents through N and F parts have opposite directions and decrease total critical current. The energy of this state increases with growth of the current. If s-layer is separated on domains, than current distribution strongly depends from which domain we choose as an electrode. If current flows to $s_0$ electrode, than the main impact in the current is provided by N channel, while the Sfs junction is suppressed by additional domain wall barrier connected in series with it. This is most energy efficient current state from chosen. Contrary, if current flows to $s_\pi$ electode, it is a π - junction with additional suppressed normal channel. In this case, for chosen parameters, it has the lowest values of critical current and the highest energy of the state.
Thus, injected current can switch system into the different states: from separated domains to homogeneous state and back.

### *Reading*




Reading of the state of Josephson Key can be implemented by vertical current through top and bottom S electrodes. In this case, weak place of the Josephson junction is located on tunnel barrier I, the critical current is much smaller than switching ones and it can't change initial state of the system. Thus, magnitude of critical current is determined only by superconductive order parameters in the vicinity of insulator I. In the state with homogeneous s-layer, current is distributed evenly over tunnel barrier, while in the case of separated domains, current through tunnel barrier consist of two channels with opposite directions of flowing. Total current in the latter state is much smaller than in the first one. Thus, system significantly changes critical current by switching and can be applied as a key element.

### *Features*

- *Switching by Josephson currents*
- *Doesn't require remagnitization of F -layer*
- *Scales in order of 100-200 nm*