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Spin-polarized transport in ferromagnetic semiconductor / diffusive semiconductor / superconductor junctions

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Motivation

Superconductivity ↔ **Ferromagnet**

<u>Appearance of the new quantum phenomena</u>

- Josephson current via ferromagnet
- Interplay between Andreev reflection or proximity effect and spin polarization

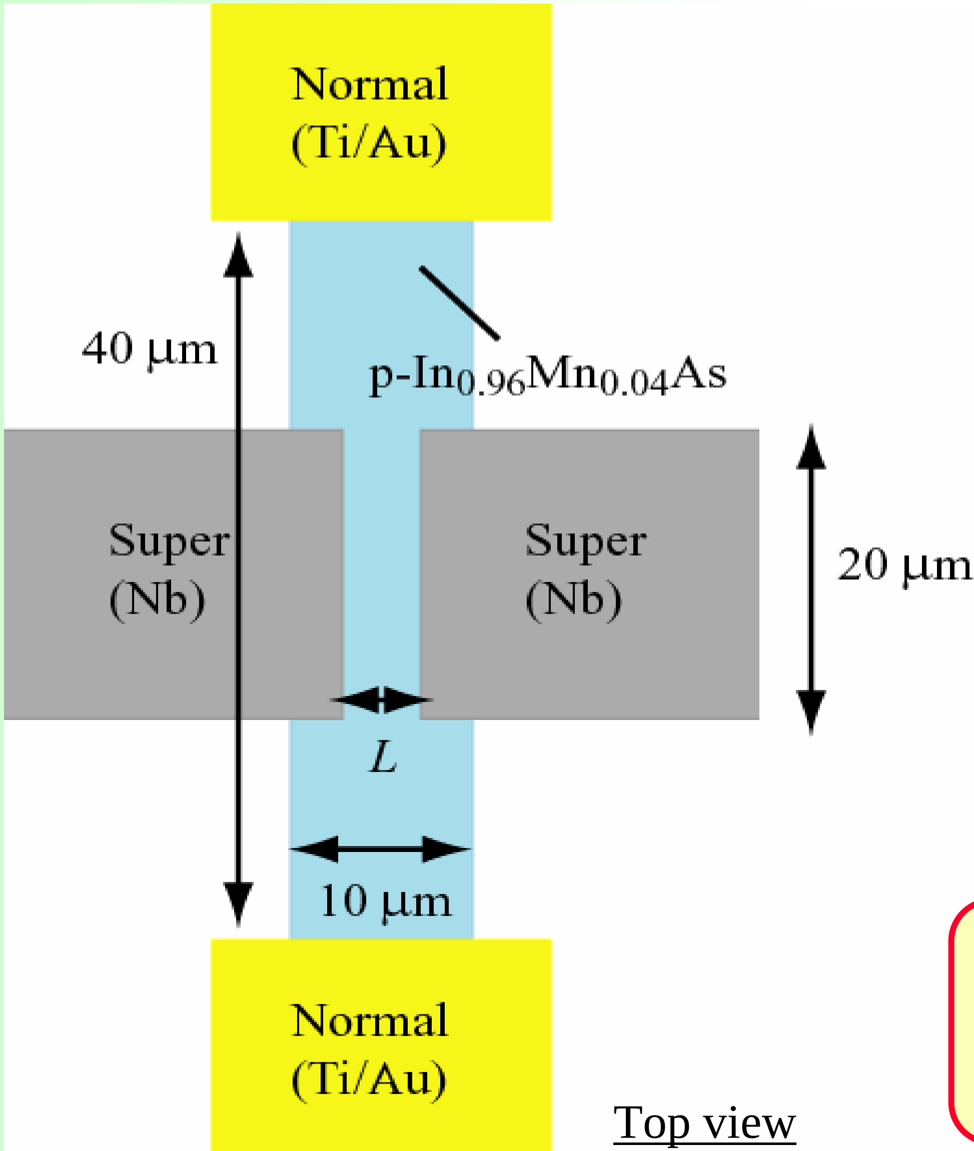
Nb/ferromagnetic p-InMnAs/Nb junction

S-F-S junction

Nb/n-InAs/ferromagnetic p-InMnAs junction

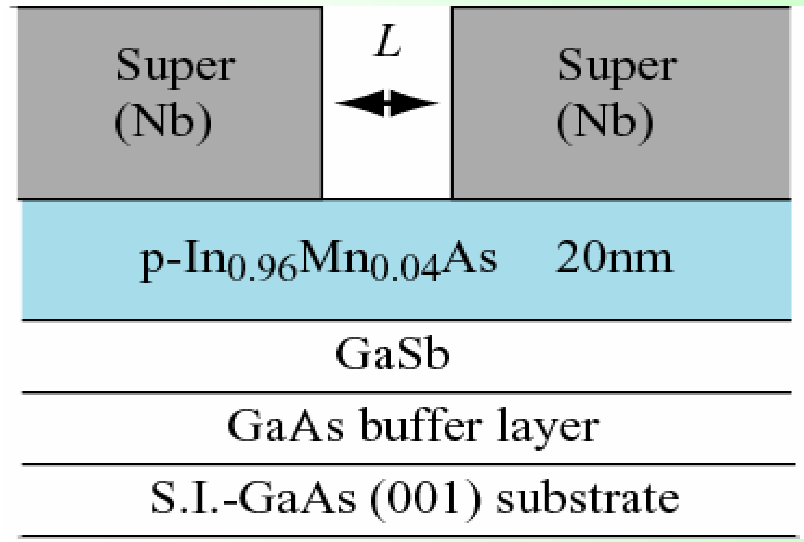
S-N-F junction

1. S-F-S junction Nb/p-InMnAs/Nb structure



Top view

L = 0.8, 10 μm

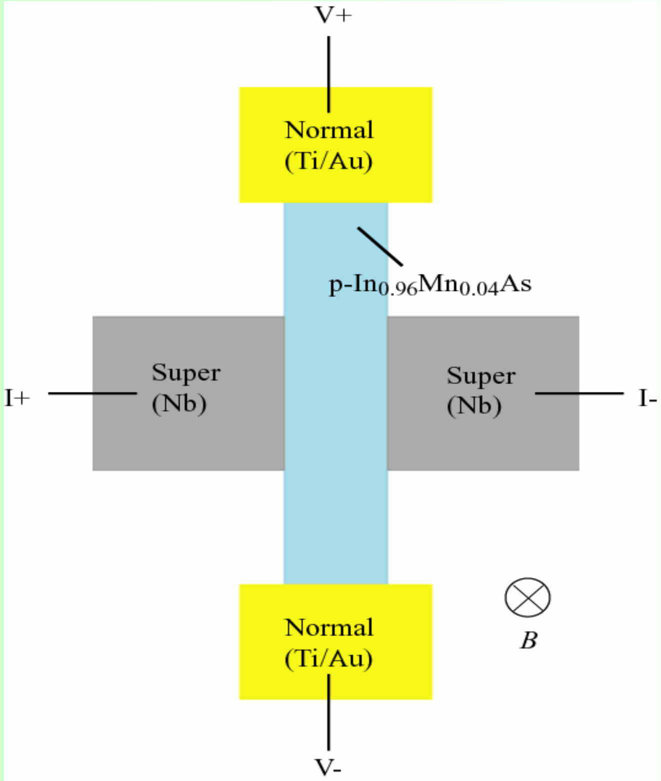


Cross-sectional view

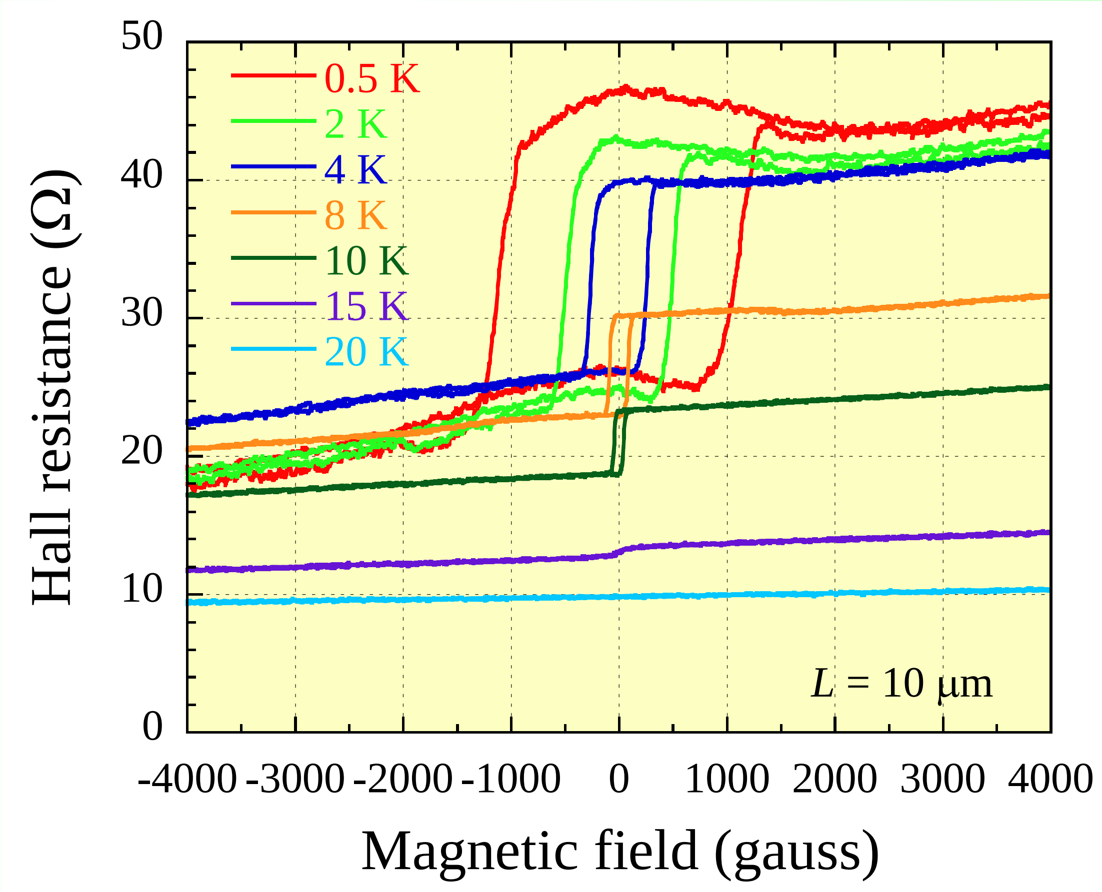
p-$In_{0.96}Mn_{0.04}As$

- P ~ 4.4 x 10^{13} (cm^{-2})
- μ_P ~ 71 (cm^2/Vs) at 0.5 K

Anomalous Hall effect

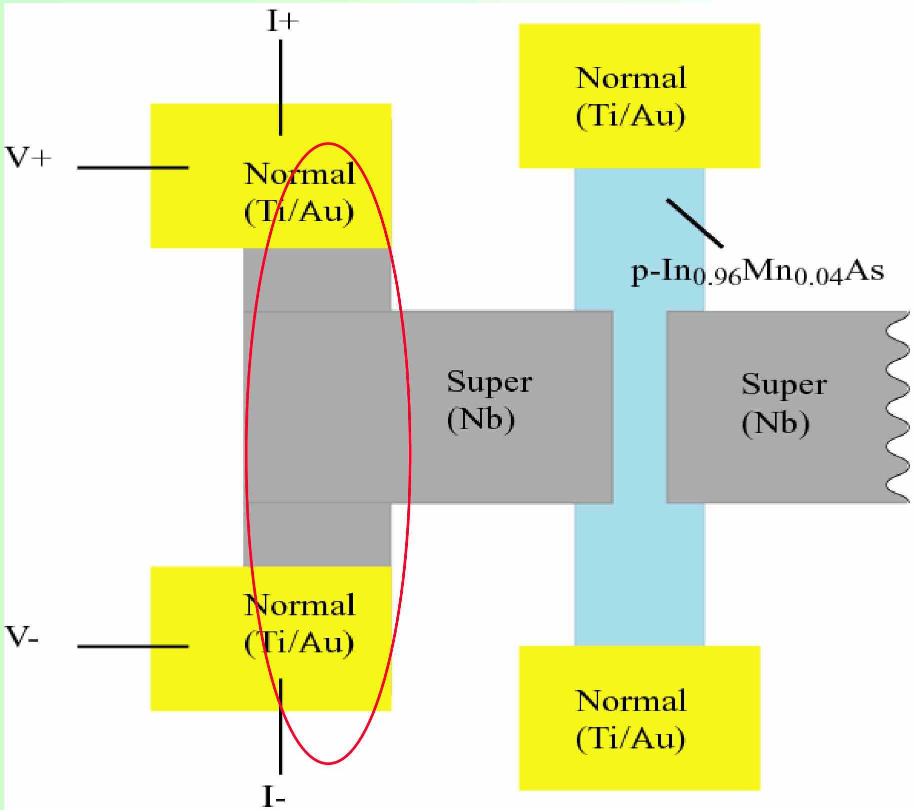


Measurement configuration

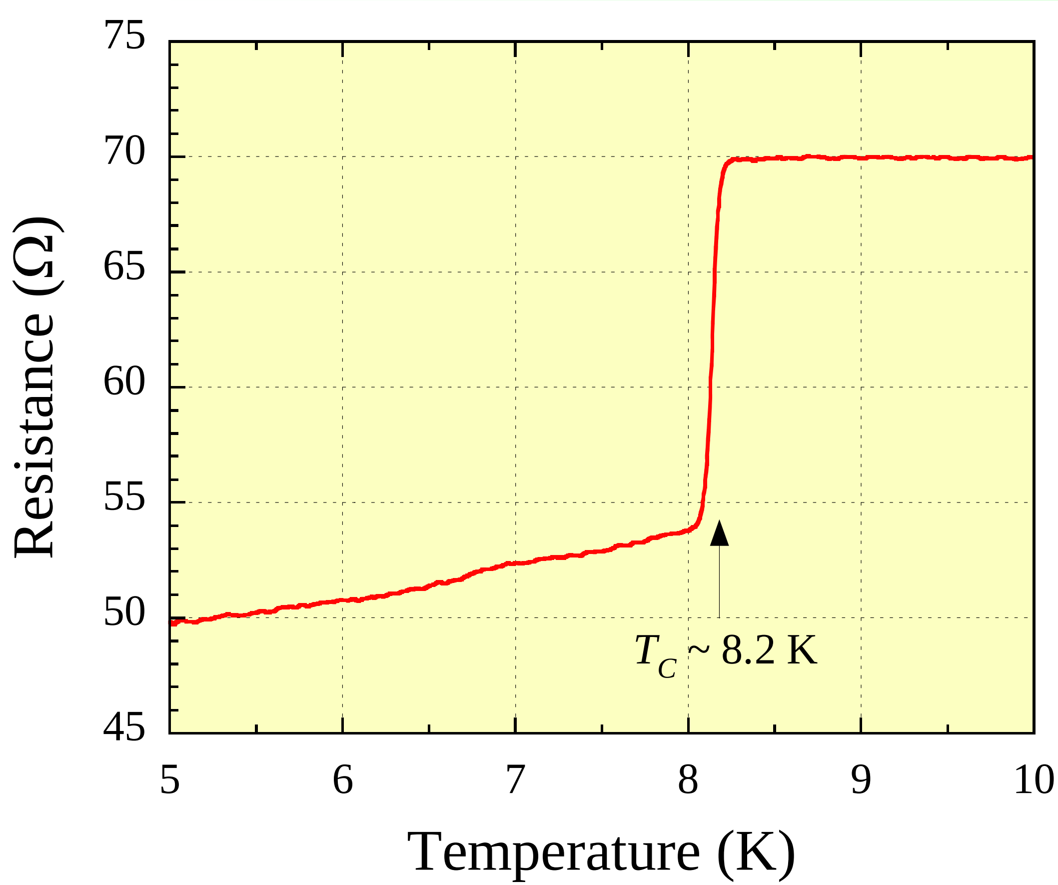


- Observation of anomalous Hall effect below ~15 K
- Reverse magnetic field is ~ 1000 gauss at 0.5 K.

T_C of Nb electrodes

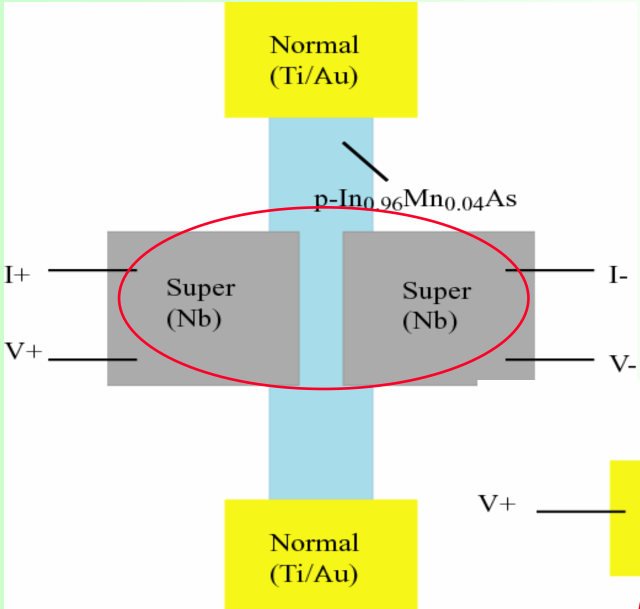


Measurement configuration

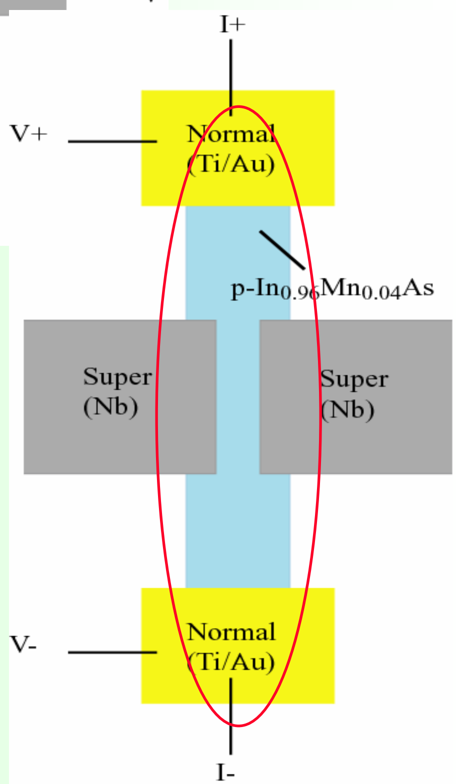


T_C ~ 8.2 K

Temperature dependence of resistance

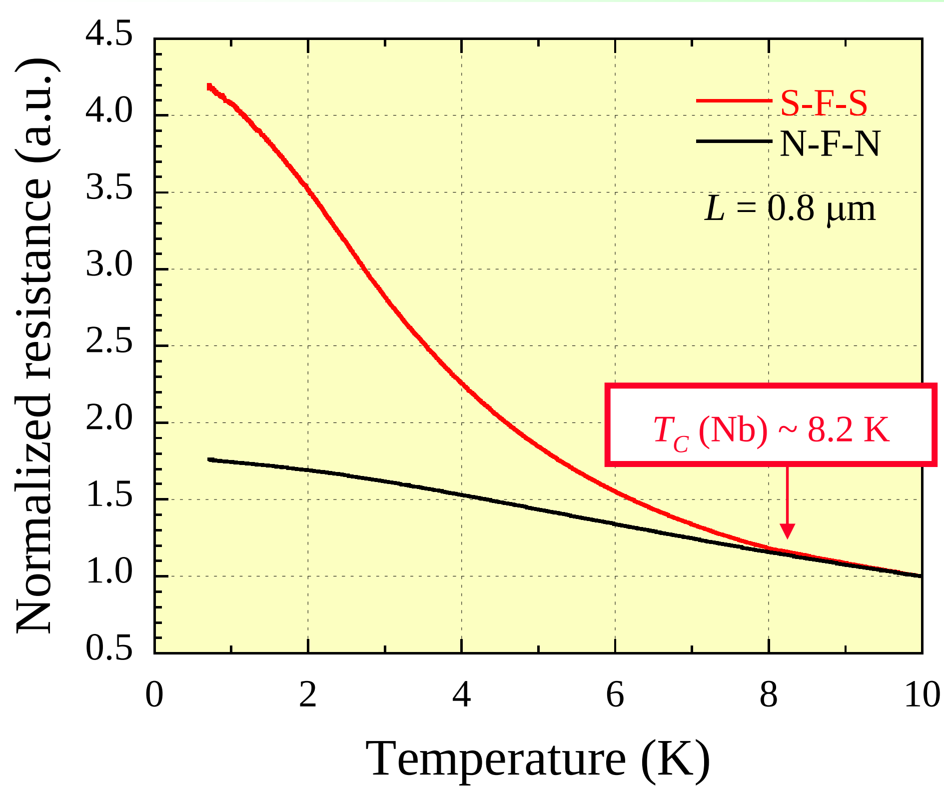


(a) S-F-S junction



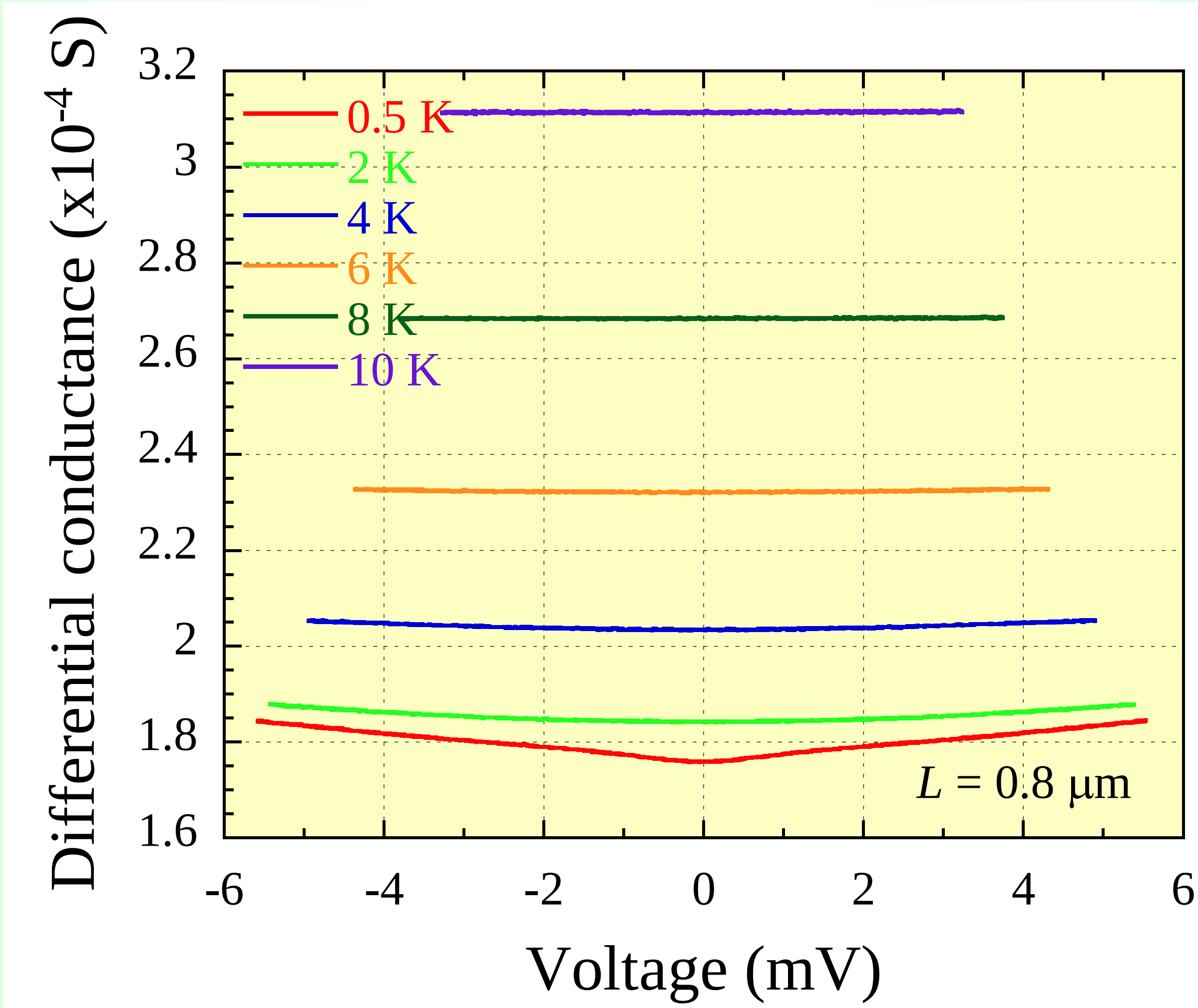
(b) N-F-N junction

<u>Measurement configuration</u>



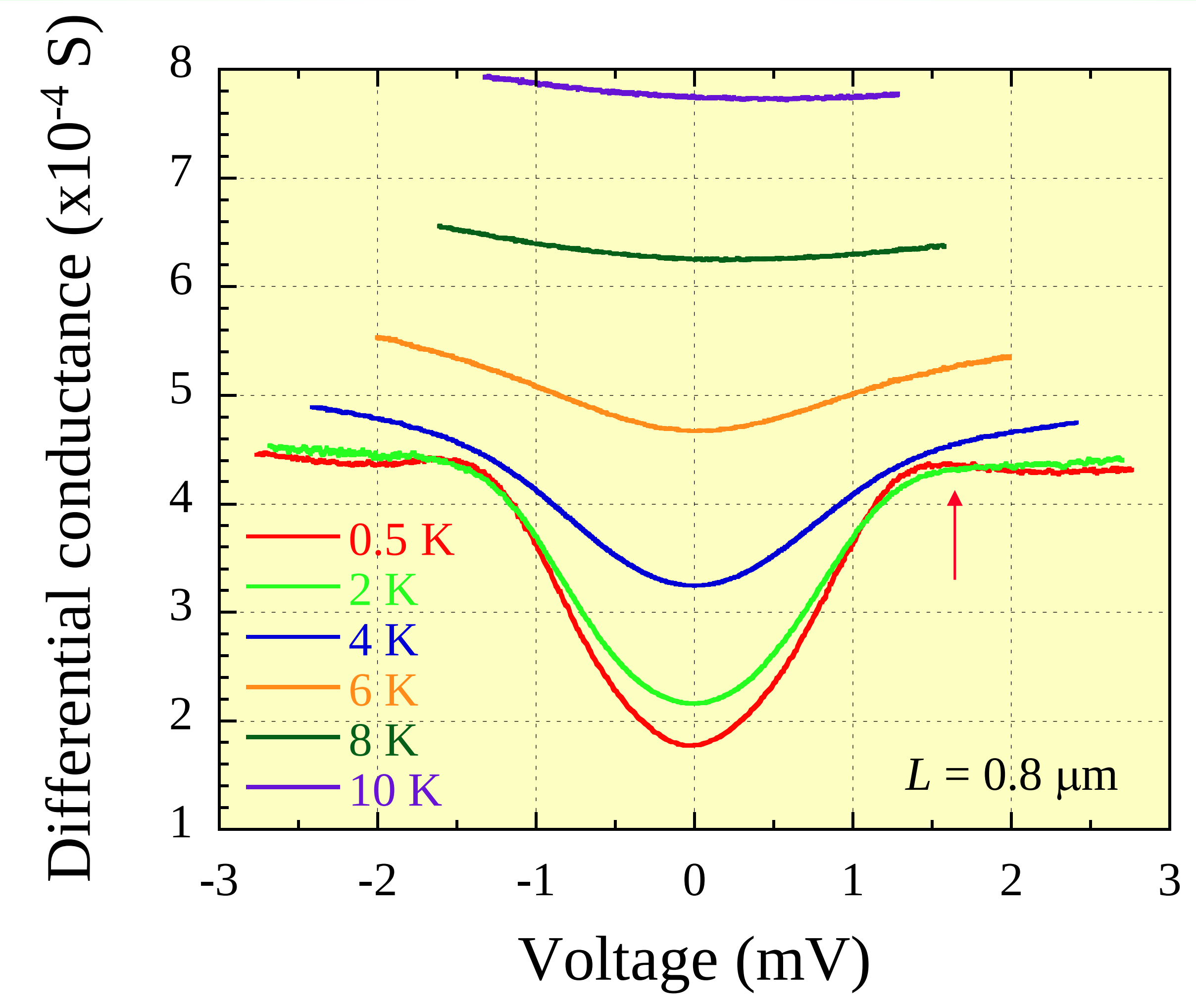
Below T_C of Nb, temperature dependence of resistance is completely different between the S-F-S and N-F-N junction.

Differential conductance in N-F-N junction



Although the weak tunneling behavior is observed in low temperatures, we have obtained nearly linear voltage-dependence.

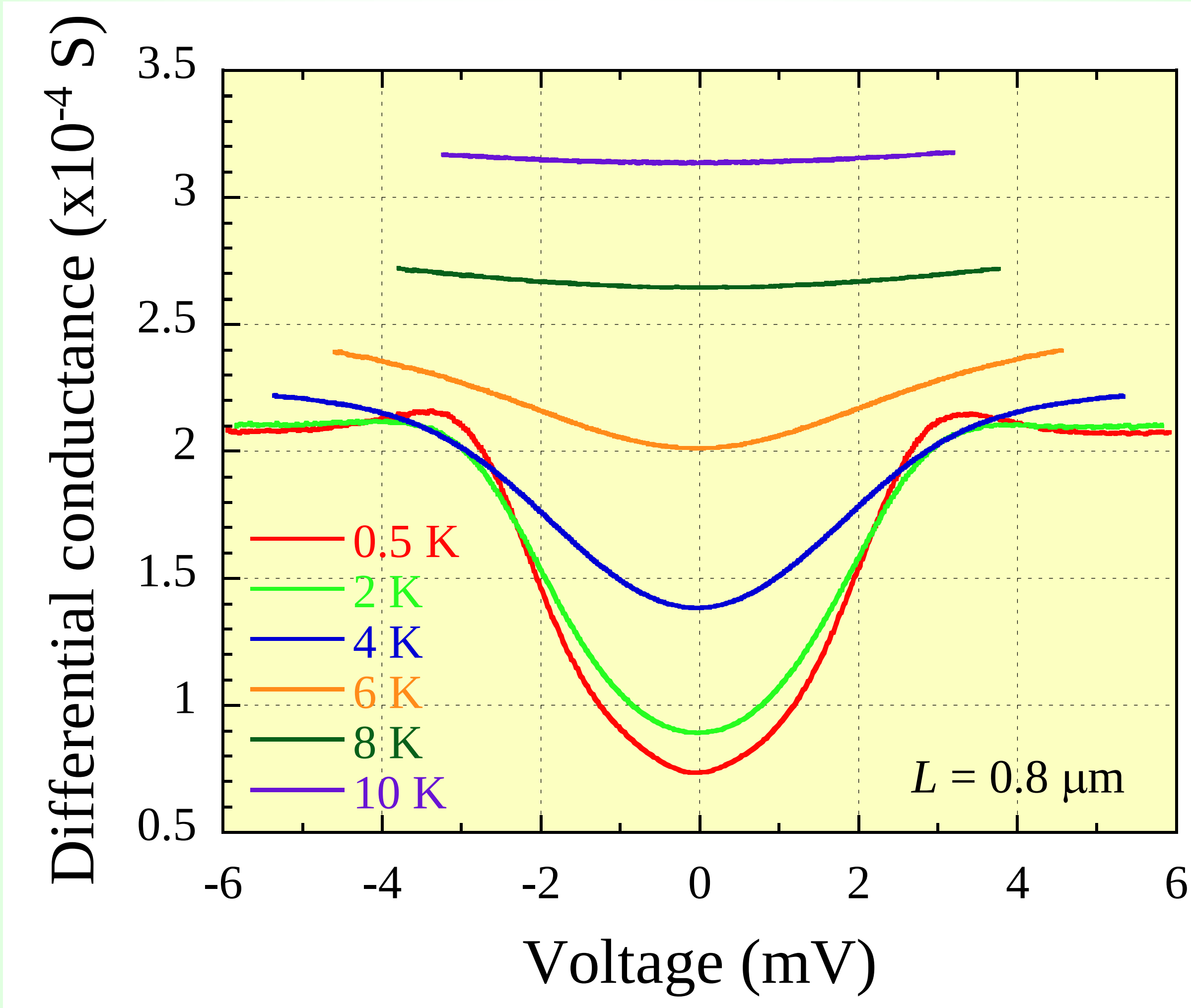
Differential conductance in S-F-N junction



We have obtained the conductance reduction within V ~ 1.5 mV.

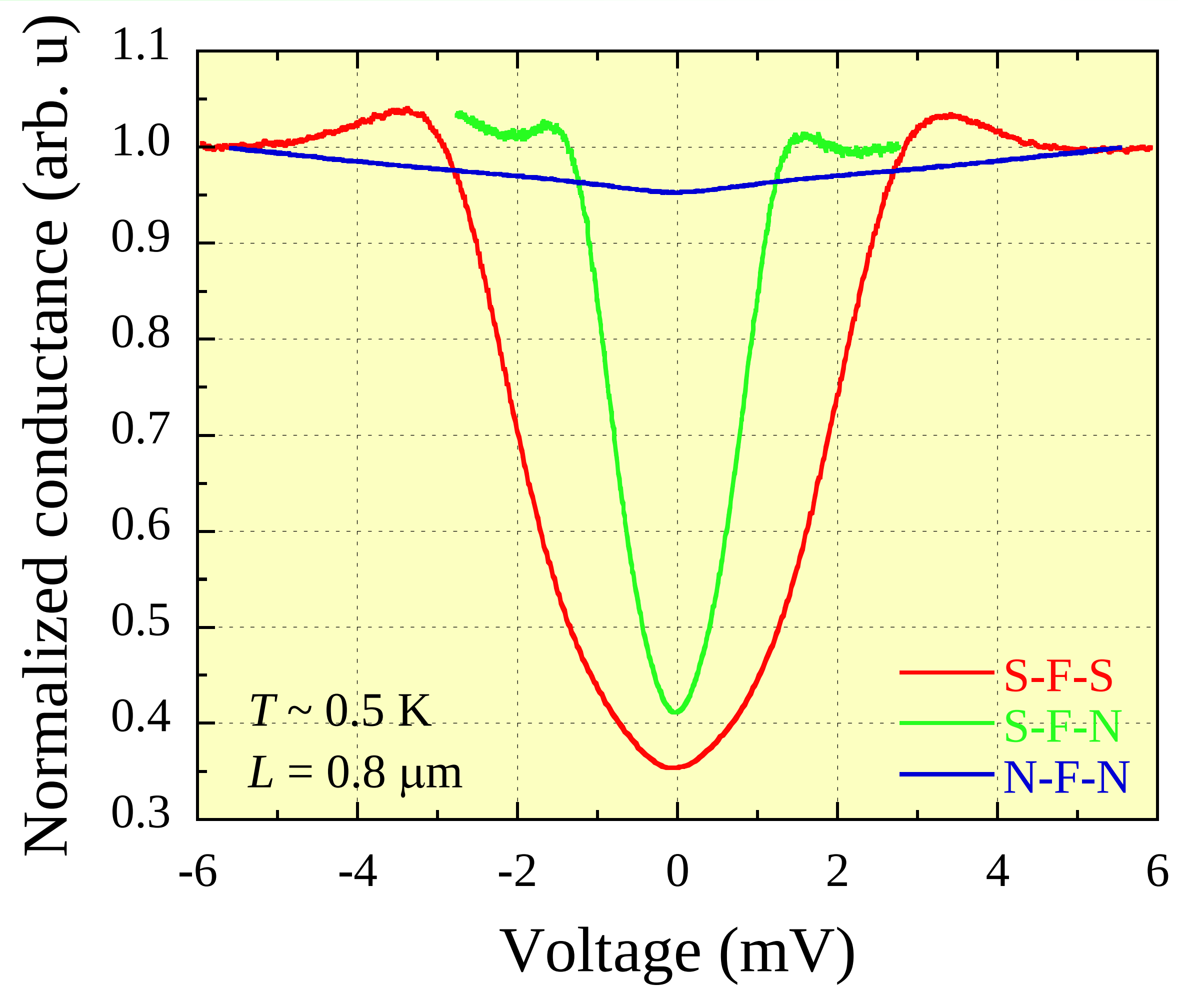
cf. Nb superconducting energy gap Δ_{Nb} ~ 1.5 meV

Differential conductance in S-F-S junction



We have obtained the conductance reduction within V ~ 3mV.

Comparison between all junctions



The conductance reduction is observed in ONLY S-F-S and S-F-N junctions.

The superconducting electrodes may affect conductance of the junction.

Discussion

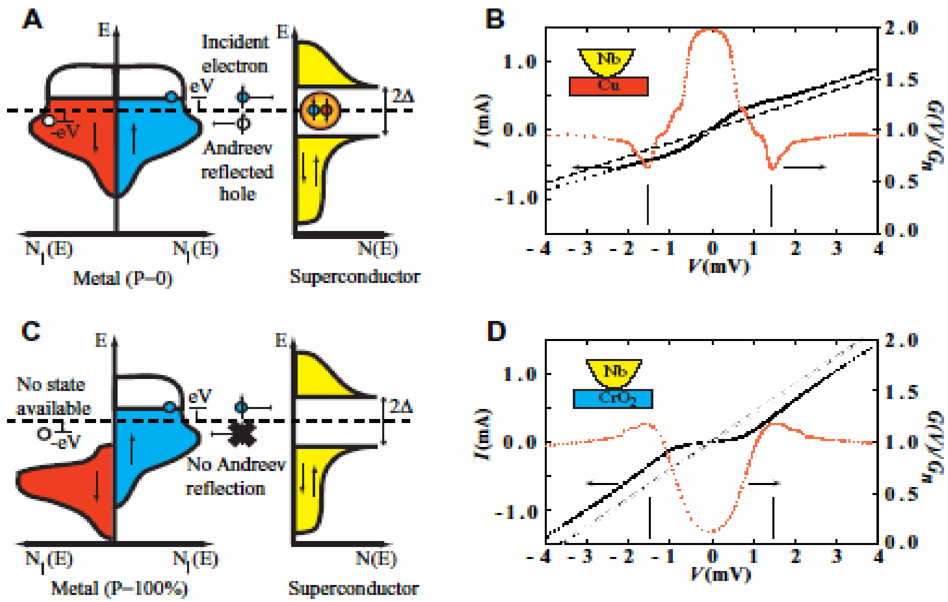


Fig. 1. Supercurrent conversion at the superconductor-metal interface for spin polarizations of P = 0 and $P \rightarrow 100\%$. (**A**) Schematic of the process for P = 0 when the Andreev reflection is unhindered by a spin minority population at E_F. The solid circles denote electrons and open circles denote holes. (**B**) Experimental measurement of the I-V and differential conductance dI/dV at T = 1.6 K via a superconducting Nb point contact on Cu. The vertical lines denote the bulk gap of Nb: $\Delta(T = 0)$ = 1.5 meV. The dashed line is the normal state I-V for a conductance of G_n = 0.194 ohm^{-1}. (**C**) Schematic of process for $P \rightarrow 100\%$ when there is no supercurrent conversion at the interface. (**D**) Experimental I-V and dI/dV at T = 1.6 K via the Nb point contact on CrO_2. The dashed line is the normal state I-V for a conductance of G_n = 0.417 ohm^{-1}.

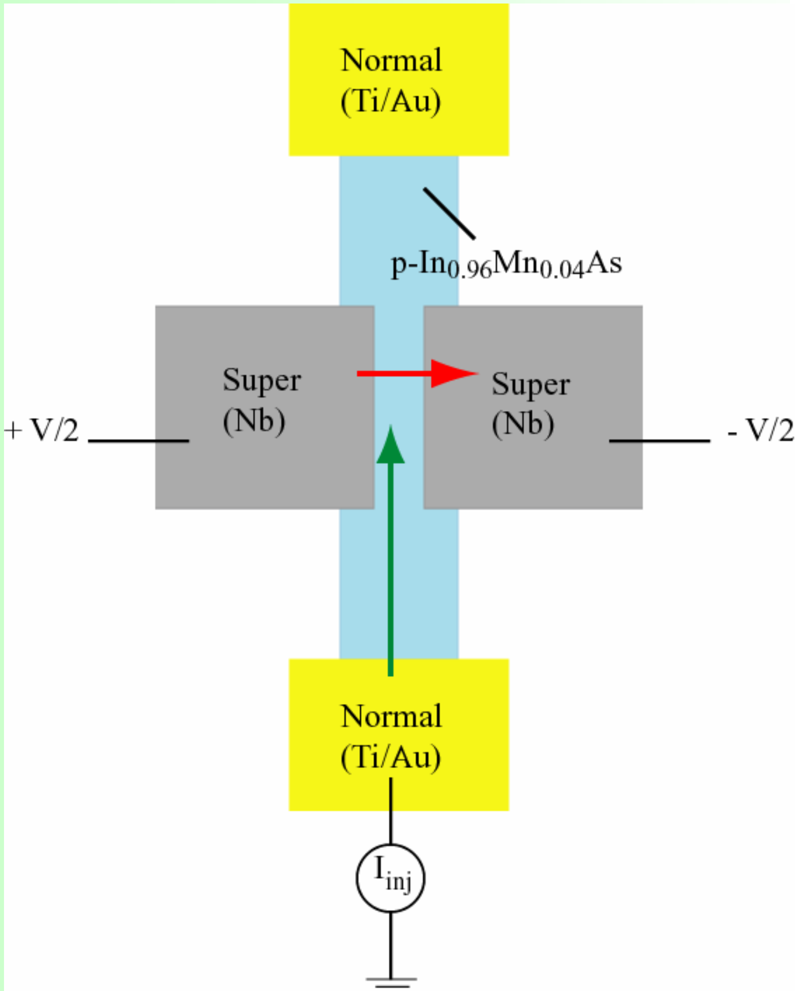
R. J. Soulen Jr. et al., Science 282, p.86 (1998)

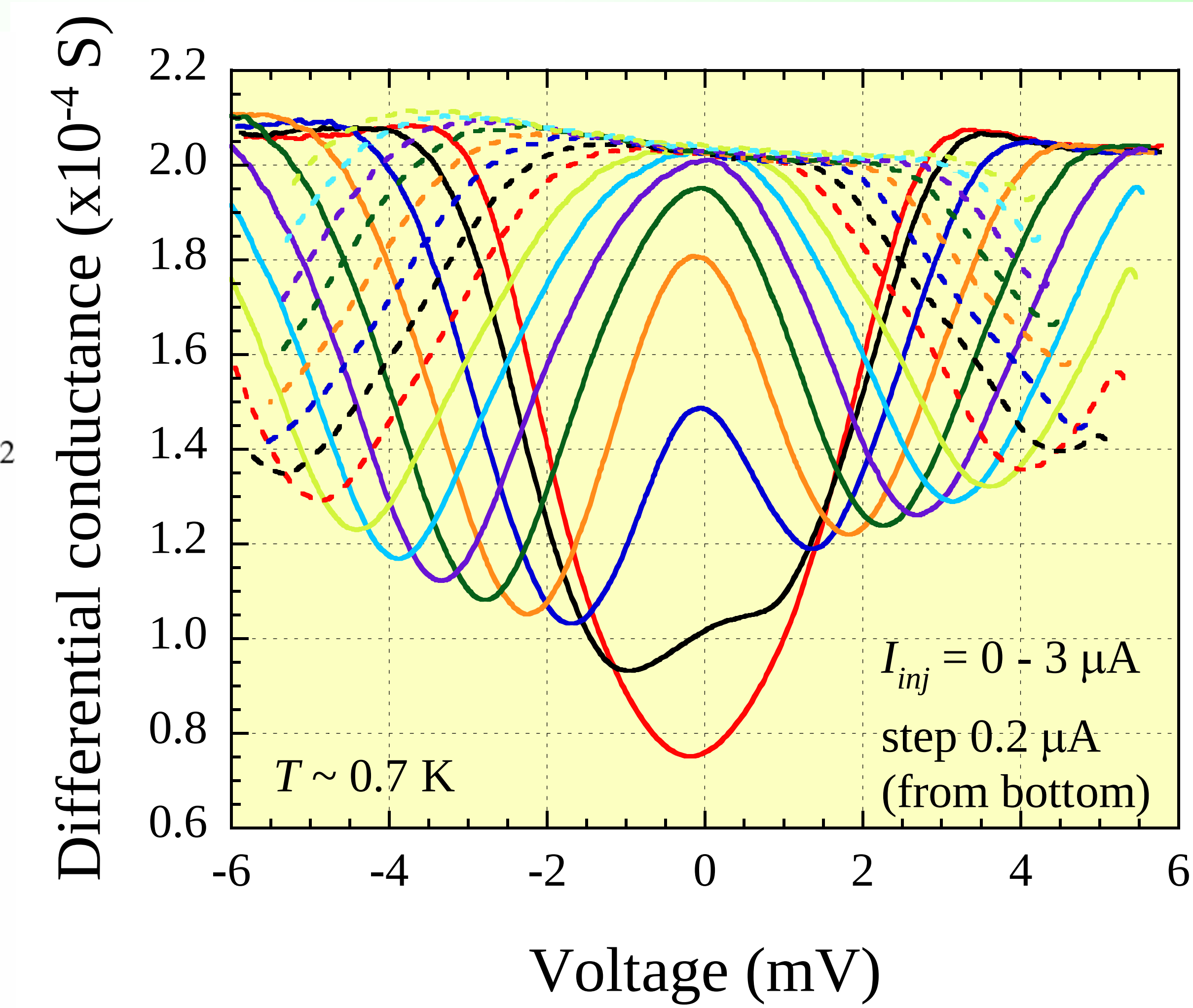
In Andreev reflection process, the incident electron requires the opposite spin electron to be removed from the N region for conversion to Cooper pair.

In case of S-F junctions, Andreev reflection is limited by the minority spin population.

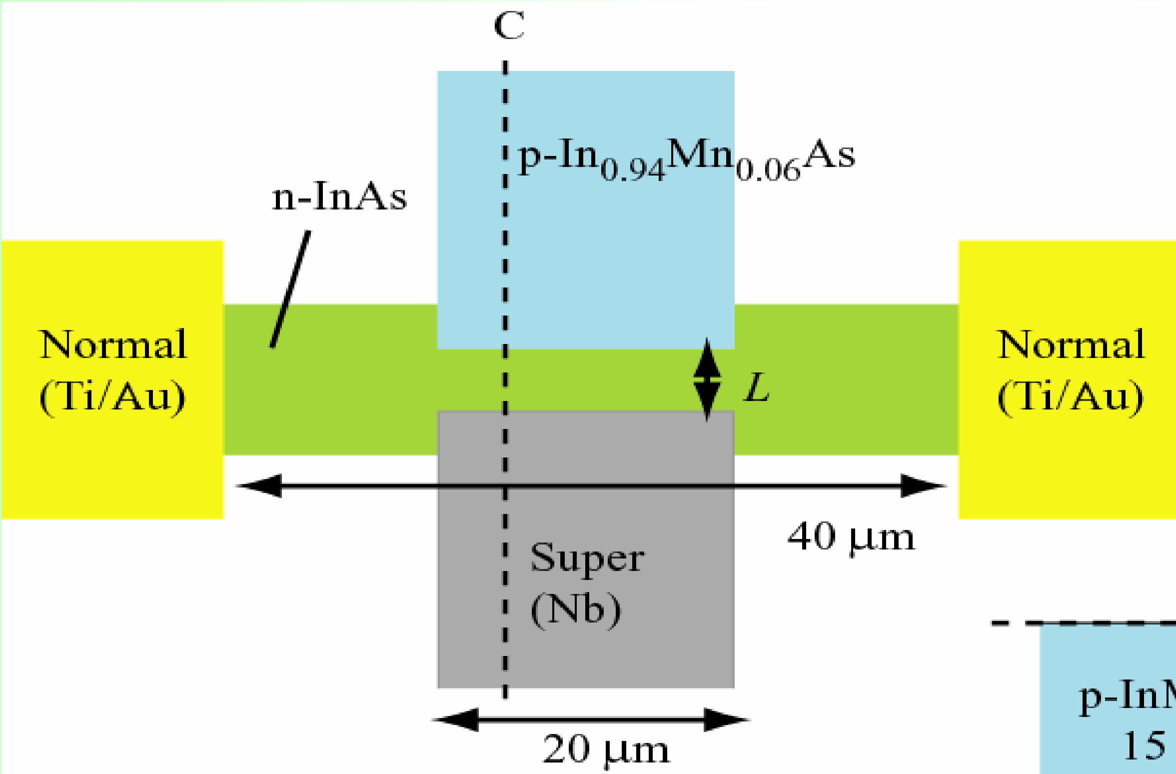
Our experimental results can be qualitatively understood by considering the suppression of Andreev reflection due to spin polarization in p-$In_{0.96}Mn_{0.04}As$.

Current injection to SFS JJ



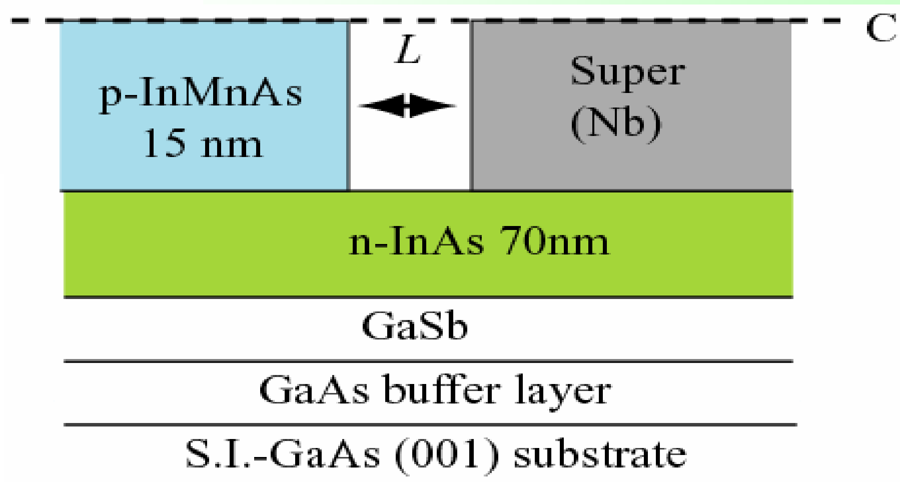


2. S-N-F junction p-InMnAs/n-InAs/Nb structure



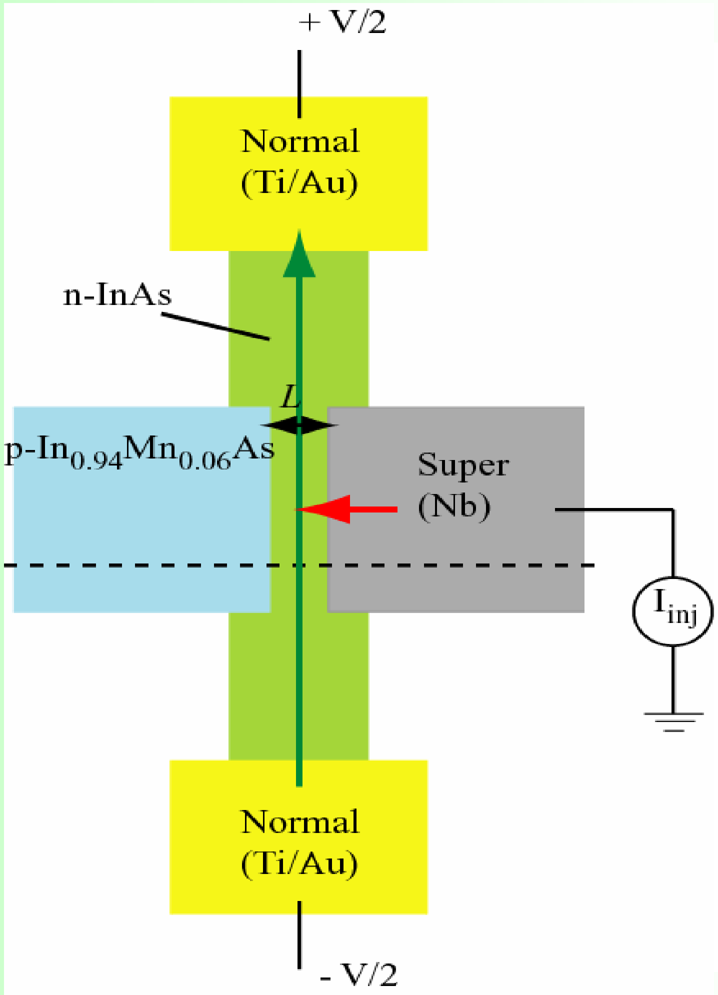
Top view

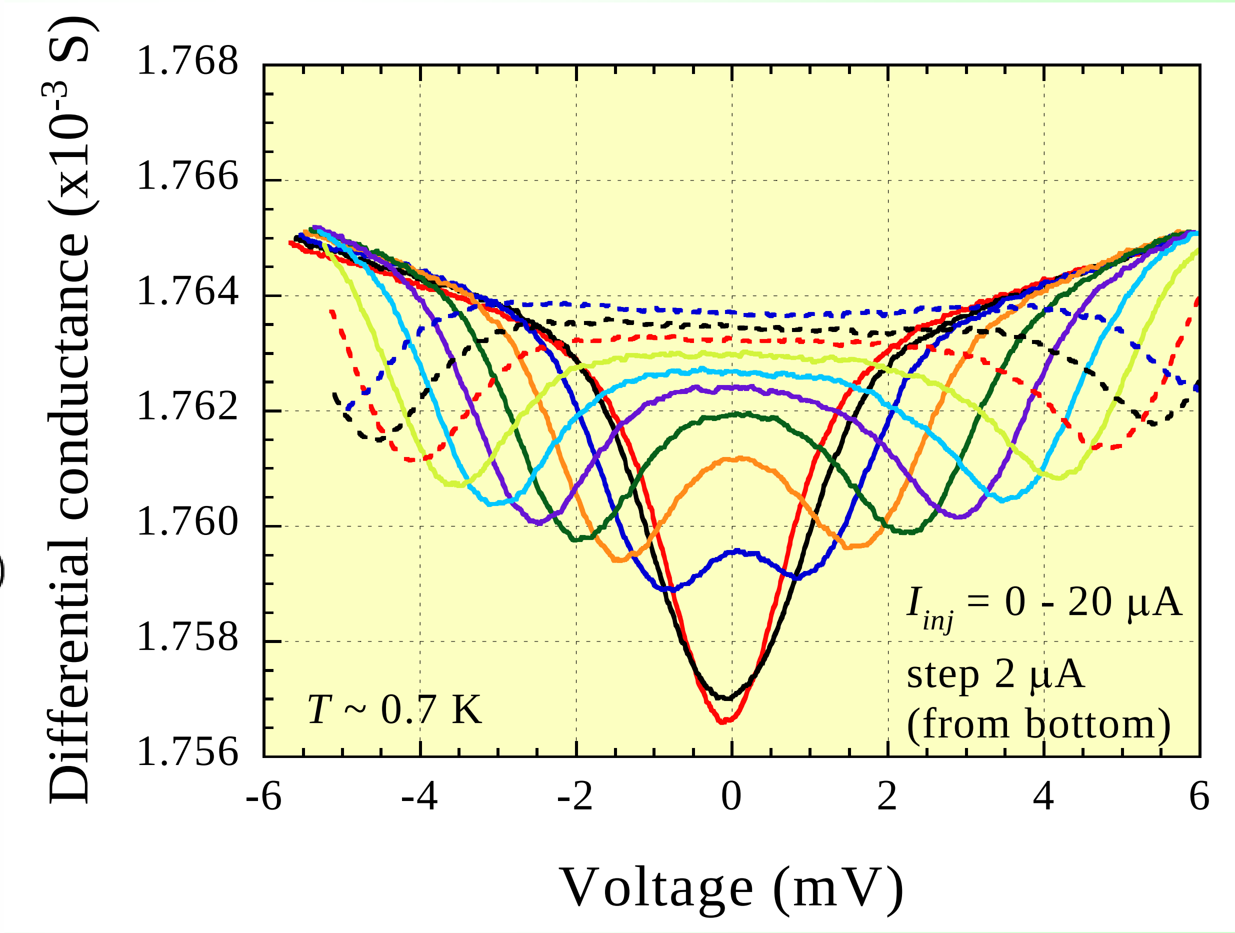
L = 0.6 µm (designed)



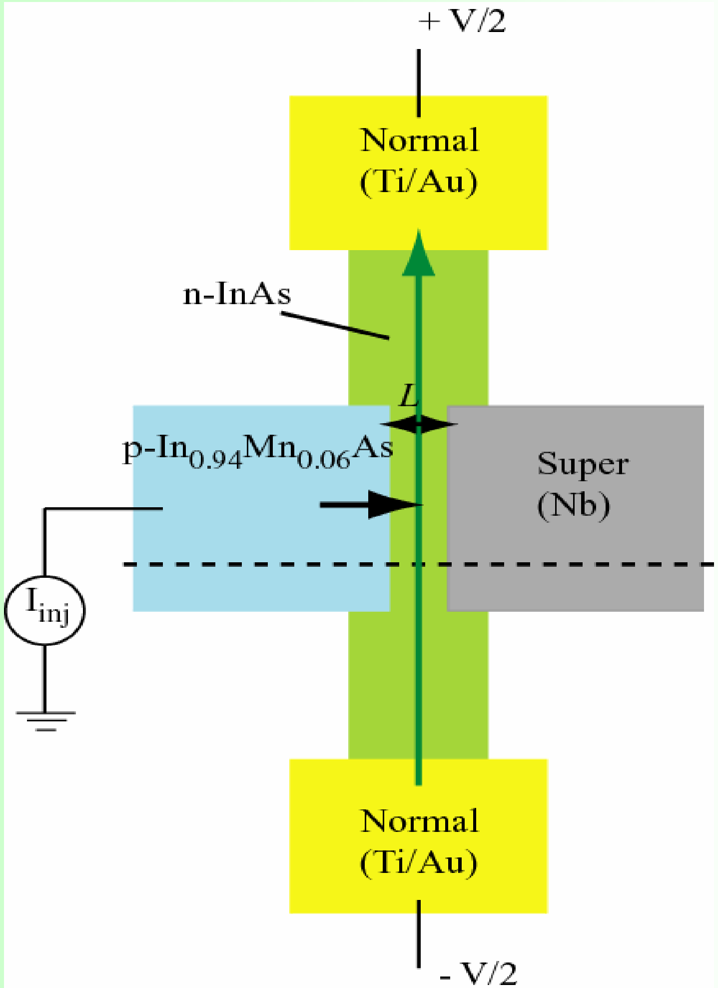
Cross-sectional view

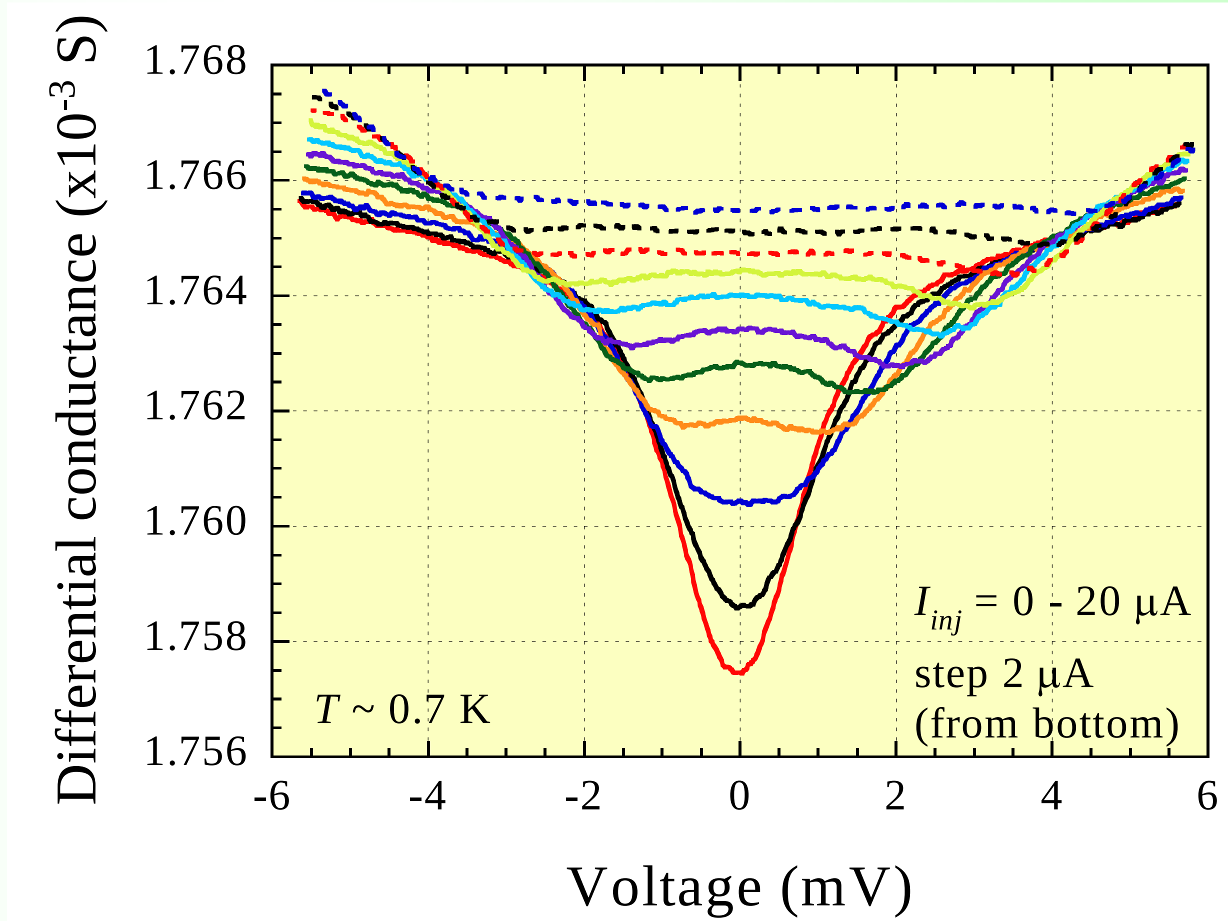
Current injection from Nb



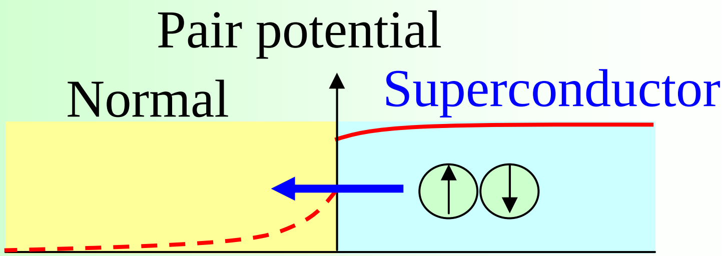


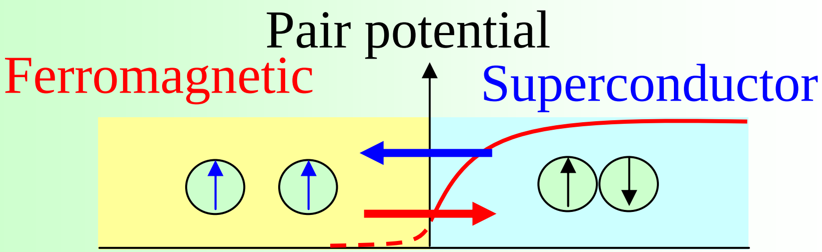
Current injection from p-InMnAs



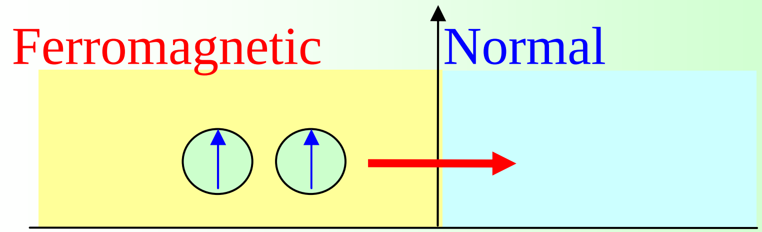


Proximity Effect



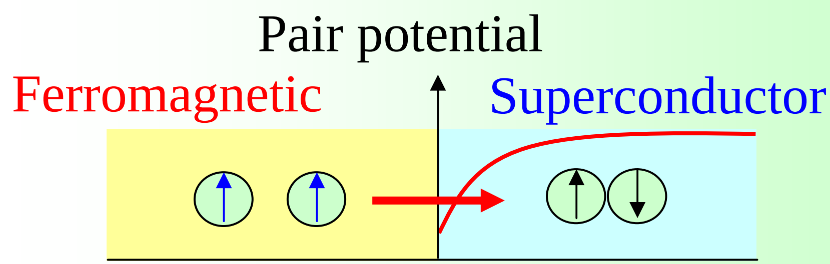


Spin Injection

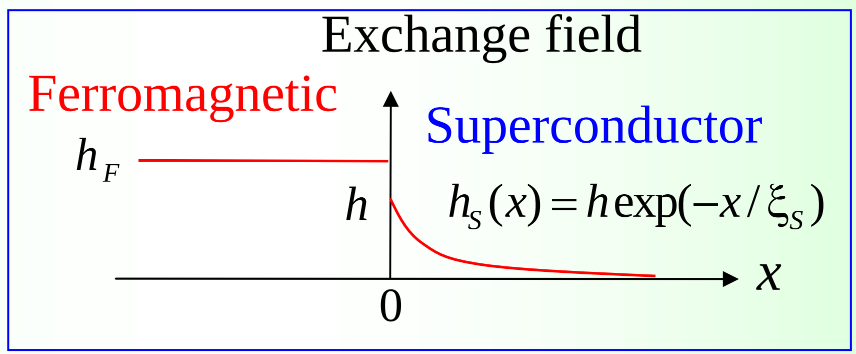


(In,Mn)As / InAs junction

Fe / Si junction

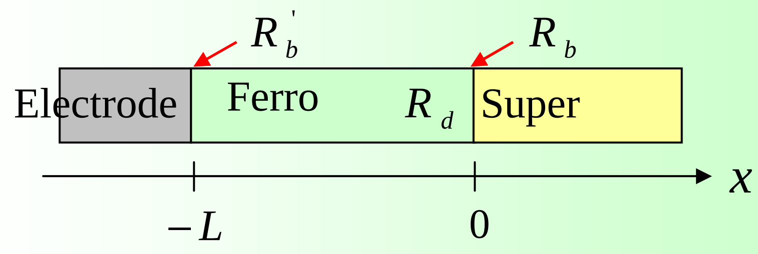


Inverse proximity effect



Theoretical Model

Mean free path $l << L$



Usadel Equation

$$D\frac{\partial}{\partial x}\left(\hat{G}\frac{\partial}{\partial x}\hat{G}\right)+i\left[\hat{H},\hat{G}\right]=0$$

$\hat{G}$:Green's function D :Diffusion constant

Hamiltonian for spins

$$\hat{H}=\begin{cases}\left(\varepsilon+(-)h_F\right)\hat{\tau}_3 & -L\le x\le 0\\ \left[\varepsilon+(-)h_S\left(x\right)\right]\hat{\tau}_3+i\Delta(x)\hat{\tau}_2 & x>0\end{cases}$$

ε : Quasiparticle energy

$\Delta(x)$: pair potential

$h_{F(S)}$: Exchange field in F(S)

$\hat{\tau}_i$: Pauri matrix $\left(i=1,2,3\right)$

Boundary condition: Conservation at the interface

$\Delta(x\to\infty)=\Delta_0$: Bulk value

Calculation Method

Green's function

Selfconsistently

Gap Equation ⇄ Usadel Eq.

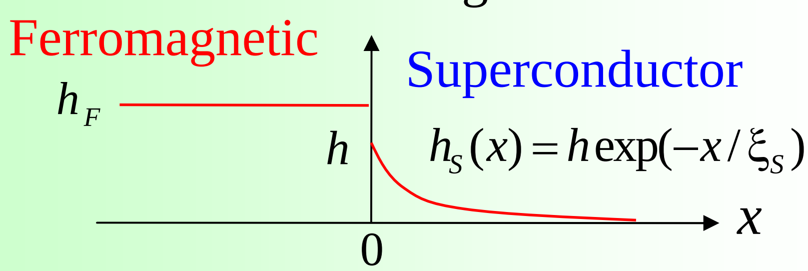
Pair potential

Golubov. et. al. (1994)

Green's function

DOS, Conductance, etc.

Exchange field



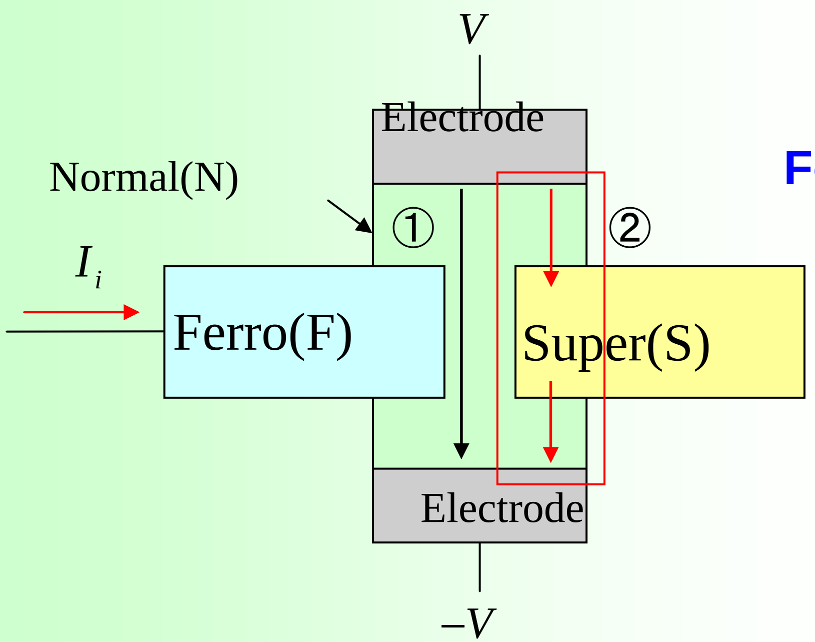
Constant h_F

Exponential decay of h_S

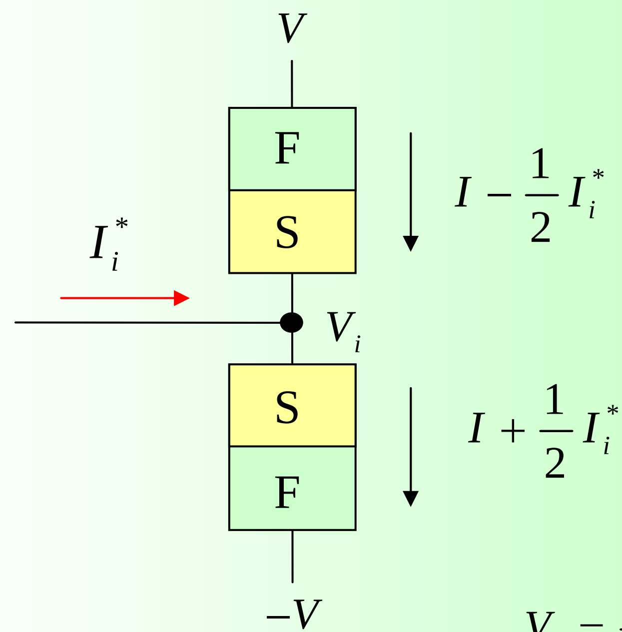
$h_F \geq h$ **Due to the barrier at the interface**

$\xi_{F(S)}$: **F(S) Coherence length**

Model for the Experiment



For path ②



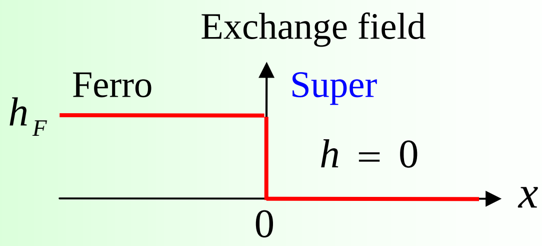
$$V_i = \frac{1}{2} R I_i^*$$

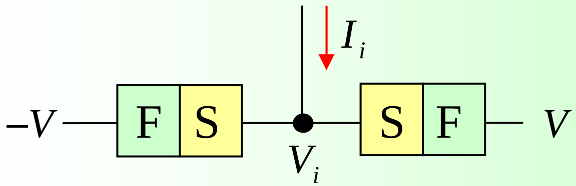
V_i Virtual voltage for the current injection

Current injection from Ferromagnetic

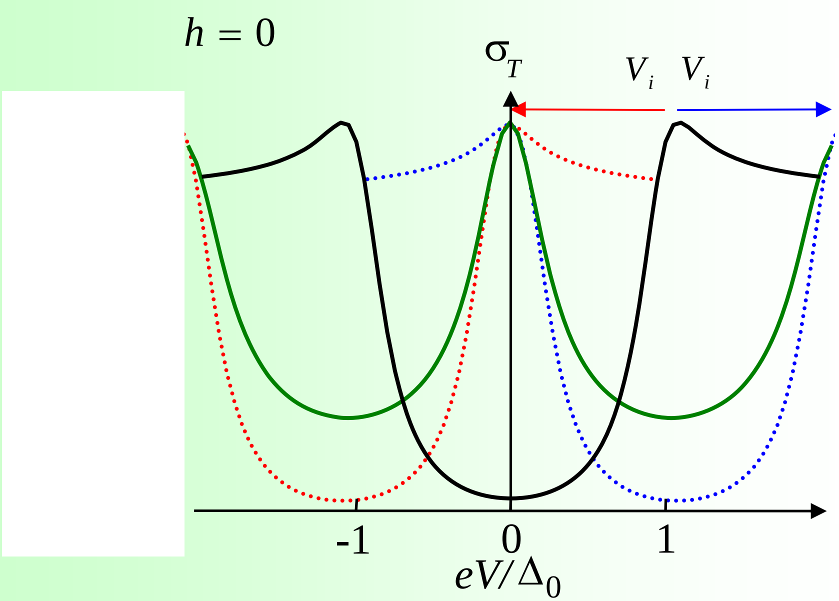
Normal ⇨ **Ferromagnetic**

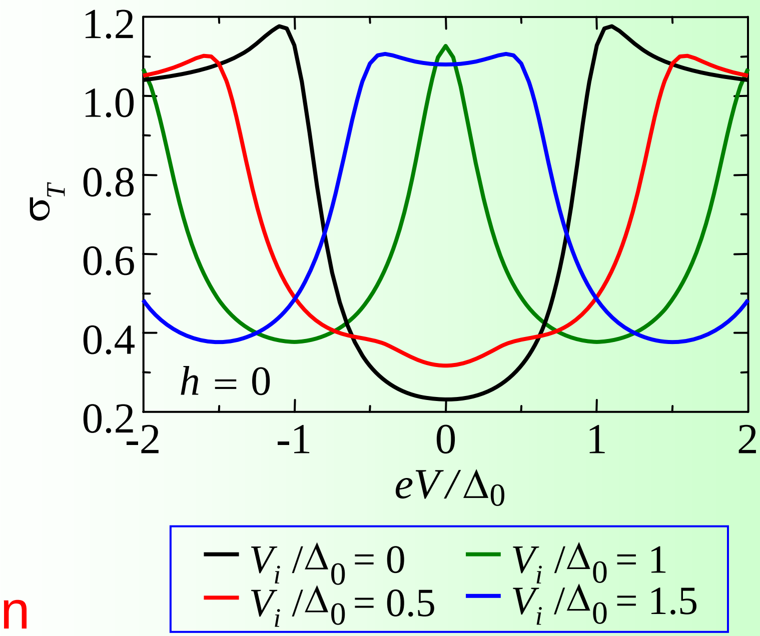
Conductance for a FS-SF junction (1)





V_i :Correnponds to current injection

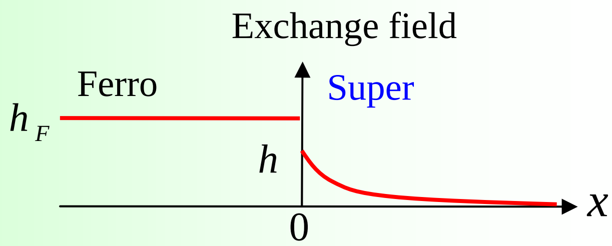


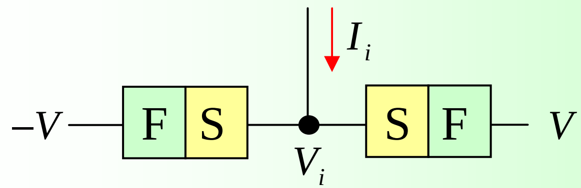


Zero-bias conductance peak by current injection

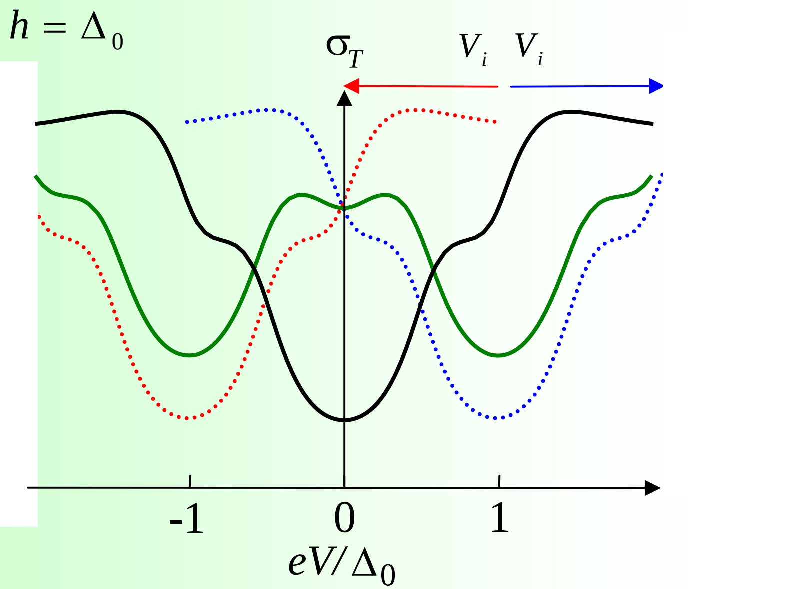
Conductance for a FS-SF junction (2)

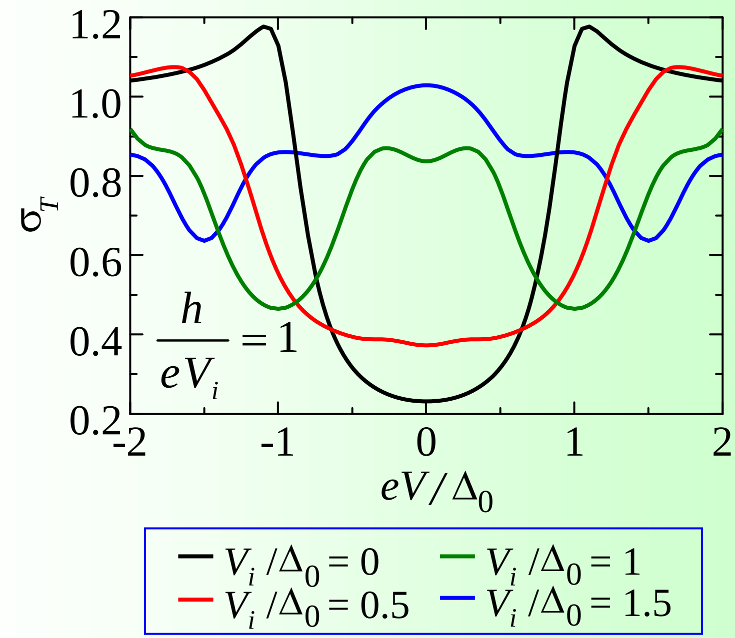
Inverse proximity effect





V_i :Corresponds to current injection



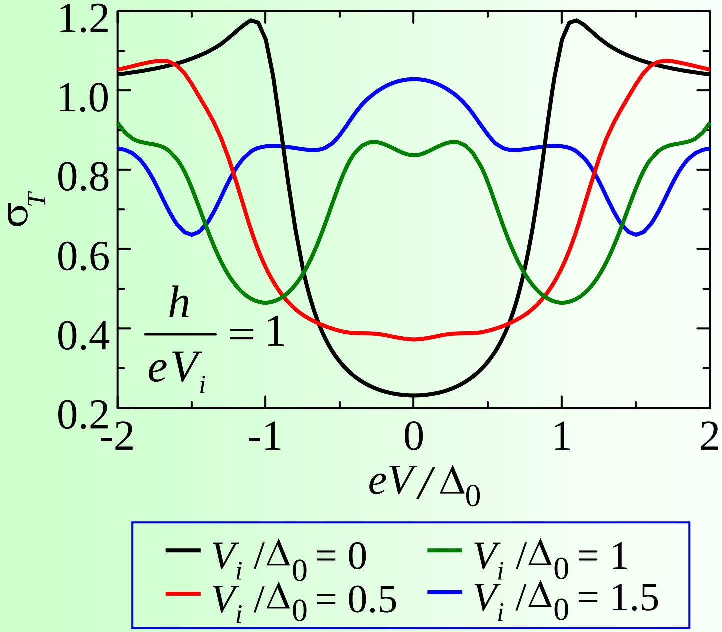


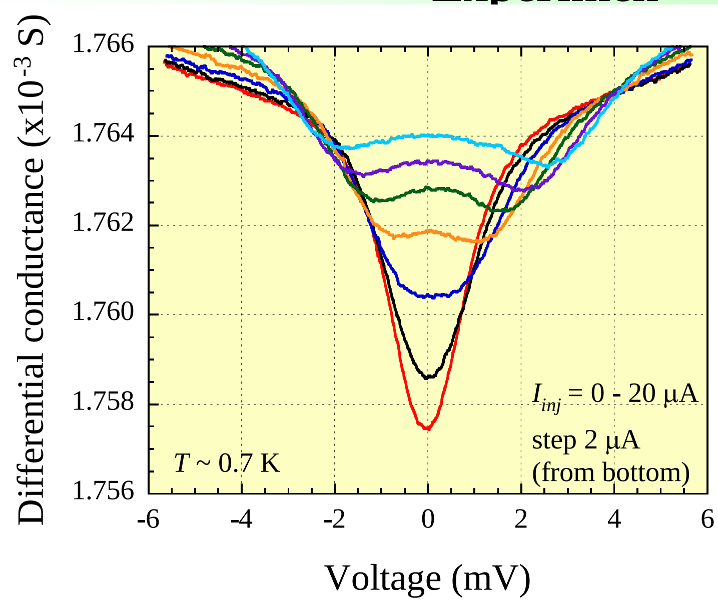
Zero bias peak is suppressed by the synergistic effect of the current injection and exchange field in the S.

Comparison with experimental results

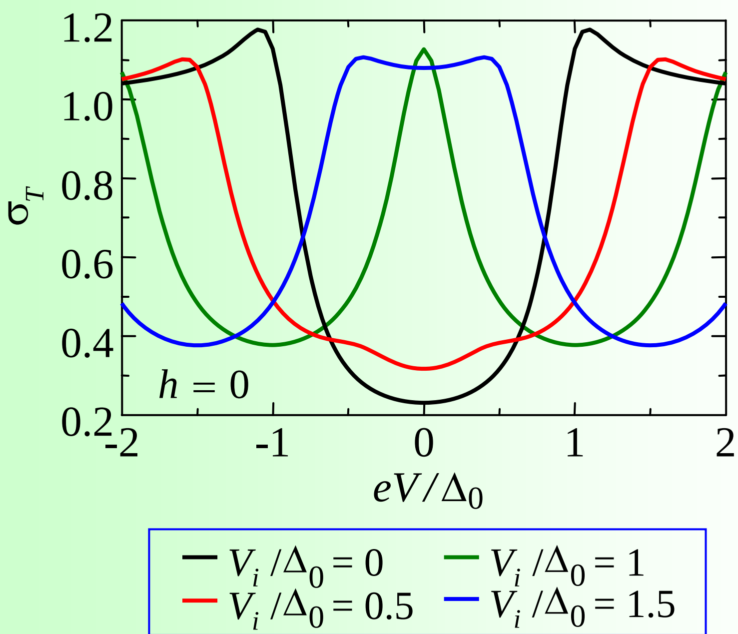
Theory

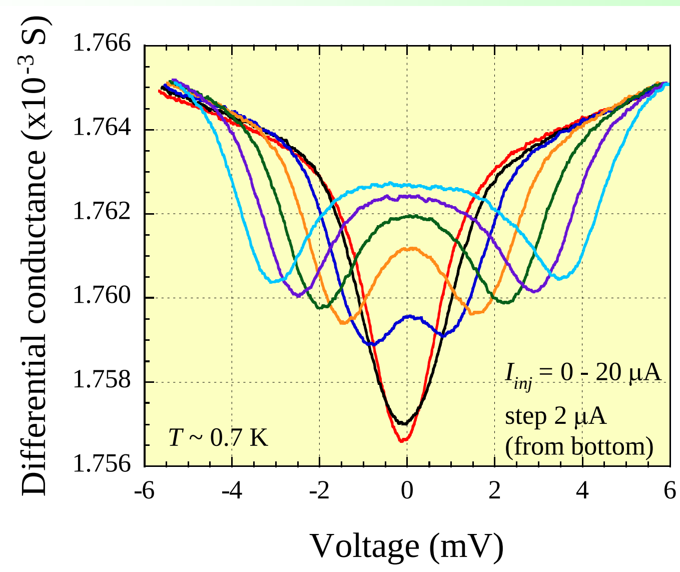
Experimen





$h_S \neq 0$





$h_S = 0$

Summary

1. Nb/**p-InMnAs**/Nb junctions.

●**Suppression of Andreev reflection due to spin polarization in p-InMnAs**

2.Nb/n-InAs/ferromagnetic p-InMnAs junction

● **We can study the conductance of two types of junctions; one is with the inverse proximity effect and the other is without the inverse effect.**

● **Our theoretical model explains both experimental results.**