JOSEPHSON EFFECT IN SN-N-NS WEAK LINKS

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For a long time SNS type variable-thickness bridges (VTB) have been considered as promising structures for applications of Josephson effect. The first theoretical estimates[I-3] have shown high I_cR_N product (I_C- is the critical current, R_N- is the normal state resistance) and much less capacitance compared with the tunnel junctions. There were two main problems in realization of VTB with suitable characteristics. The first was the requirement to provide a presize submicrometer gap between superconducting electrodes. The second was the difficulty with an optimum choice of S- and N-materials for a junction because of the lack of theoretical calculations related with this question. These were the main reasons for great development of tunnel junction technology.

Now it is possible to fabricate VTBs due to the technology achievements in reproducing nanometer elements. Experimental VTBs with 0.I μ weak link lengths have been described in recent works[4,5]. However, only the capabilities of submicrometer technology were demonstrated in these works and there was no discussion of electrodes and span materials' choice.

The aim of the report is to ground theoretically the materials' choice for SNS type VTBs which provide a relatively high I_CR_N product ($\gtrsim$ I mV) and to verify a theory by experimental investigation of Nb-Al-Nb VTB.

SN-N-NS microbridge model

Fig.I shows a scheme of bridge geometry where SN-sandwich is used as an electrode. This fact leads to nonuniform superconducting gap suppression in S-layer by proximity effect with N-layer. By its turn the critical current I_C decreases. Influence of the proximity effect [6] depends on the parameter.

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$$\gamma_M = \frac{\sigma_N \xi_S}{\sigma_S \xi_N} \cdot \frac{d_N}{\xi_N} , \qquad (I)$$

where $\sigma_{S,N}$ - are the normal state conductivities, $\xi_{S,N}$ - are the coherence lengths of S- and N- materials, d_N - thickness of N-layer ($d_N \ll \xi_N$). When $\gamma_M \ll 1$ a proximity effect is small and critical current is equal to maximum value I_o[6]. For arbitrary the critical current I_c have been numerically calculated in "dirty" limit. Fig.2 shows $I_c(T)$ functions for long ($L \gg \xi_N$, L-weak link length) bridges. In the average temperature range $T \approx T_c/2$ for $\gamma_M \approx I$ I_c/I_o is equal to 0.I and 0.0I at $T \approx T_c$. Both for short ($L \lesssim \xi_N$) and long bridges critical current is greately suppresed in the critical temperature range $T \approx T_c$. Calculations have shown that for the most interesting range of the bridge parameters $L \lesssim 3\xi_N$, $T \approx T_c/2$ a critical current is about two times less as compared to the maximum value I_o under condition.

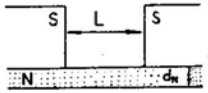

Fig.I. A scheme geometry of SN-N-NS VTB. L-weak link length, d_N- N -layer thickness. ($d_N \ll \xi_N$).

$$\gamma_M \lesssim 0.3 \qquad (2)$$

Bridge parameters' optimization

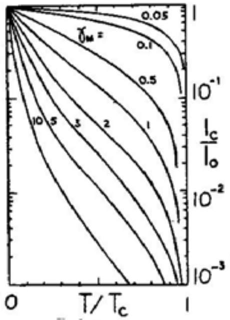

Fig.2. Normalized critical current I_c/I_o in $L \gg \xi_N$ limit vs reduced temperature T/T_c for various γ_M. I_o = $64\pi T/(eR_N) * \Delta_\infty^2 \cdot L/\xi_N \cdot \exp(-L/\xi_N) \cdot \{\pi T + \Delta^* + \sqrt{2}[\Delta^*(\Delta^* + \pi T)]^{1/2}\}^{-2}$ - critical current for $\gamma_M = 0$[6] where $\Delta^* = [(\pi T)^2 + \Delta_\infty^2]^{1/2}$, Δ_∞ - equilibrium order parameter in S-layer ($K_B = \hbar = I$).

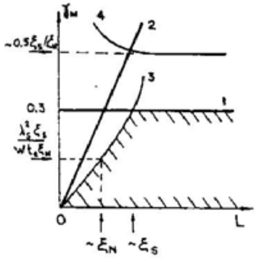

Fig.3. The weak link parameters range (dashed) on (γ_M,L) plane where one can neglect: I - proximity effect, 2 - superconductivity suppression in electrodes by current, 3 - cross-section superconducting phase difference accumulation, 4 - back influence of proximity effect between span and composit SN electrode. Solid lines separate the regions where the above effects can be neglected, the dashed field is intersection of these regions.

The main parameters of the Josephson junctions are the characteristic voltage $V_c = I_c R_N$, normal state resistance R_N and capacitance which is very small for VTBs. We shall find the conditions under which V_c is high and R_N is not very small. Note that the optimum parameter values depend on optimization criteria.

For the first criterion we have chosen a slightness of the proximity effect because it is the main in suppressing $I_c R_N$. For example, we shall require $I_c R_N$ reduction by a factor of two. This criterion is suitable because it results in $V_c \gtrsim I$mV that is desirable for the most applications. As is shown it is true under condition (2).

All previous considerations have been carried out under the following assumptions: I) there is no superconductivity suppres-

S / N	Pb	Nb	Nb_3Sn	NbN
Si* (monocryst.) $n^* \approx 10^{20} cm^{-3}$	$3 \cdot 10^{-3}$	$3 \cdot 10^{-3}$	$2 \cdot 10^{-2}$	$4 \cdot 10^{-2}$
Si* (policryst.) $n^* \approx 10^{20} cm^{-3}$	$3 \cdot 10^{-2}$	$3 \cdot 10^{-2}$	0.2	0.4
n-InAs* $n^* = 3 \cdot 10^{18} cm^{-3}$	$5 \cdot 10^{-3}$	$4 \cdot 10^{-3}$	$3 \cdot 10^{-2}$	$7 \cdot 10^{-2}$

Table I. Parameter $\gamma = (\sigma_N \xi_S)/(\sigma_S \xi_N)$ for widely used S and N materials[7].

in the case of bridge over superconducting screen. Here λ_s - is the magnetic field penetration depth for S-metal, W - bridge width, t_e - effective distance from the superconducting screen.

We have estimated the widely used materials. Table I shows the parameter $\gamma = (\sigma_N \xi_S)/(\sigma_S \xi_N)$ for several S and N pairs. Assuming $W \approx 2\mu$, $t_e \approx 0.3\mu$ for the best pair Nb-InAs [8] one obtains a restriction on γ

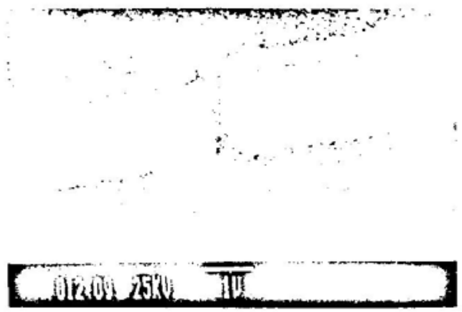

Fig.5. Microphotograph of Nb-Al-Nb microbridge.

$$\gamma \lesssim \frac{\lambda_S^2 \xi_S}{W t_e \xi_N} \cdot \frac{\xi_N}{d_N} \approx 10^{-3} \cdot \frac{\xi_N}{d_N} , \qquad (4)$$

which yields

$$d_N \lesssim (d_N)_{max} \approx 0.3 \xi_N \approx 20 \, nm. \qquad (5)$$

Such a bridge should have a normal state resistance $R_N \approx 10\Omega$.

These estimates show that for fabricating VTB with high $I_c R_N$ it is necessary to produce thin (~ 20 - 40 nm) normal conductivity higholmic layers. The fabrication of such layers by means of evaporation or ion impurity implantation to semiconductor surface is on the verge of possibilities of these methods. Thus, it is desirable to find the new methods for a fabrication such layers, providing small γ_M . The outlook materials are monocrystal n-type layers with a high carrier mobility on the semiconductor surface obtained by molecular beam epithaxy. However

sion in electrodes by current, 2)back influence of proximity effect between span and composit SN-electrode is slight, 3) junction is concentrated one. As is was shown [7] these three conditions give rise to additional restrictions on γ_M . Fig.3 shows the range of the junction parameters on (γ_M ,L) plane (dashed) where one can neglect all above processes decreasing $I_c R_N$. It

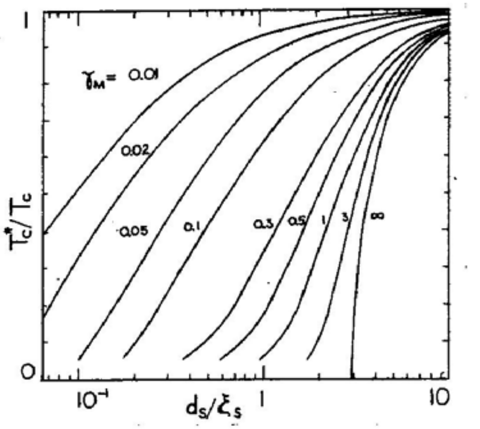

Fig.4. Critical temperature T_c^* of SN sandwich with thin N-layer ($d_N \ll \xi_N$) as a function S-layer thickness d_S for various γ_M . T_c - critical temperature of the bulk S-metal, T_{CN}= 0.

remains to choose optimum weak link length L. Because of exponential $V_c(L)$ decreasing at $L \gg \xi_N$ it is nesessary to take $L \lesssim \xi_N$. However, very small L leads to strong restrictions on γ_M and also to small R_N ($R_N \backsim L$). The optimum length is $L \approx \xi_N$ from the point of view of these contradictory requirements. Parameter is to be very small

$$\gamma_M \lesssim \frac{\lambda_S^2 \xi_S}{W t_e \xi_N} \qquad (3)$$

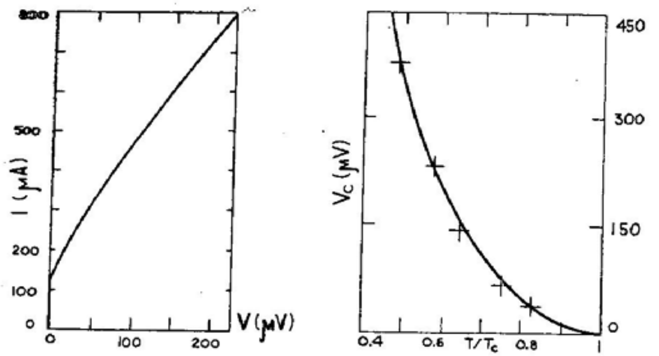

Fig.6. (a) I-V curve of Nb-Al-Nb VTB with $L \approx 0.25\,\mu$, $R_N \approx 0.4\,\Omega$ at T=5.5 K, (b) $V_c(T)$ - function for the same bridge; solid line - theoretical calculation for $L \lesssim \xi_N$ and $\gamma_M = 1$ [6].

one should have a direct method for measuring γ_M without one of the parameters constructed. One of such methods is critical temperature measurement for SN-sandwich.

It is known that critical temperature T_c^* of SN-sandwich depends on S-layer thickness d_s because of the proximity effect. For $d_s \to 0$ limit T_c^* decreases to zero and for $d_s \to \infty$ T_c^* aspire to that of bulk superconductor. Fig.4 shows that $T_c^*(d_s)$ functions calculated [9] for orbitrary γ_M. It is possible to estimate γ_M for a certain S-N pair by comparison the experimental and theoretical data. For the purpose ξ_s can be easily obtained from measurements of critical magnetic field Hc_2 of S metal near T_c.

Experiment

We have fabricated Nb-Al-Nb VTBs. Aluminium films with the thickness 50-60nm were deposited on Si-substrate with the temperature 200-230°C. It was used a lift off technique for Al strip sampling. Nb films were deposited at high vacuum 10^{-9}- 10^{-10}Torr with the thickness 200 nm, T_c= 9.0K, and R_{300}/R_{10}= 6. The preferable sample technique for Nb is plasma-chemical etching (PCE) because the contrary ion or ion-chemical etching PCE doesn't make

worse a superconductivity of Nb film s and Al film structure. Fir.5 shows a microphotograph of Nb-Al-Nb VTB with $d_N \approx 0.05\,\mu$, $d_s \approx 0.2\,\mu$, $W \approx 1\,\mu$, $L \approx 0.25\,\mu$. Nevertheless, Nb-Al-Nb bridge is not optimum, it allows examination of our theory.

DC properties

Our junctions had a normal state resistance R_N in the range $0.1 \div 1\,\Omega$. Typical I-V curve is shown in Fig.6a. I_cR_N product is about $50\,\mu V$ at T = 5.5 K. Such a low I_cR_N was caused by strong proximity effect ($\sigma_s \approx 0.1\sigma_N$). It means that γ_M is relatively great in our case. We can estimate γ_M by fitting $V_c(T)$ function (Fig.6b) which yields $\gamma_M \approx 1$. Believing $L \sim \xi_N$ and $\Delta_0/e \approx 1$ mV for Nb one can obtain the coherence length for Al $\xi_N \approx 0.1\,\mu$ which is in a good agreement with $\xi_N \approx (\xi_0 d_N)^{1/2} \approx 0.3\,\mu$, where $\xi_0 = 1.6\,\mu$ is the theoretical coherence length value for a clean bulk aluminium.

Conclusion

The variable thickness bridges are the promising structures for applications of the Josephson effect. For production of the optimum VTB it is necessary to choose S and N materials providing small γ_M. Degenerated narrow gap semiconductors are the suitable materials for a bridge span. Nevertheless, our theory does not describe the peculiarities of the carrier transport in semiconductors; it correctly reflects the processes which affects the weak link properties.

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