Laboratori Nazionali di Frascati

LNF-87/93(NT)
16 Ottobre 1987

F. Celani:

SUPERCONDUTTIVITA' E GIUNZIONI TUNNEL SUPERCONDUTTRICI COME RIVELATORI DI PARTICELLE IONIZZANTI

Copie Trasparenze

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Premessa

Vista l'attualità della superconduttività (assegnazione del premio Nobel a Müller e Bednorz), si terrà nei Laboratori Nazionali di Frascati dell'INFN un seminario informativo, aperto a tutto il personale ricercatore, tecnico e amministrativo, a metà novembre 1987.

Per una più agevole comprensione dell'argomento, si ritiene utile la diffusione di trasparenze già utilizzate, con soddisfacenti risultati durante il "Florence Workshop on Imaging Detectors" tenutosi a Firenze il 21-22 Settembre 1987.

Le trasparenze sono parte in Italiano (introduzione alla Superconduttività, Effetto Tunnel, Giunzioni Superconduttrici, Conclusioni), e parte in Inglese (discussione sui Limiti alla Risoluzione Intrinseca delle Giunzioni Superconduttrici Tunnel Utilizzate quali Rivelatori di Particelle Ionizzanti). La parte in inglese é praticamente copia degli "Invited Papers" e "Contributed Paper" presentati dal Dr. F. Celani a:

"Low Temperature 18" di Kyoto" - 19/26 Agosto 1987;
"International Superconductive Electronic Conference" di Tokyo" - 28/29 Agosto 1987.

GIUNZIONI TUNNEL SUPERCONDUTTRICI COME RIVELATORI DI PARTICELLE IONIZZANTI: PROBLEMATICHE E PROSPETTIVE.

F. CELANI ISTITUTO NAZIONALE FISICA NUCLEARE,
LABORATORI NAZIONALI DI FRASCATI.

S. PACE DIPARTIMENTO DI FISICA, UNIVERSITÀ DI
SALERNO

+∼10 COLLABORATORI (INFN, UNIV. SALERNO, MPI, CNR)

"FLORENCE WORKSHOP ON IMAGING DETECTORS"
FIRENZE, 21÷22 SETTEMBRE 1987-

SUPERCONDUTTIVITÀ

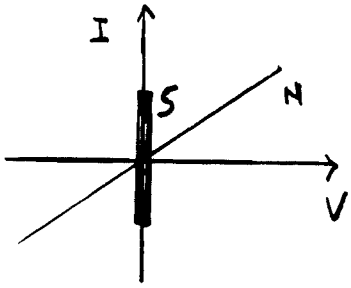
EFFETTI MACROSCOPICI: TUTTI GLI EFFETTI VALGONO SOLO SE $T < T_c$ (temperatura critica)

1) NON VALE LA LEGGE DI OHM ($V = IR$), $R > 0$ per $\forall T$.

SCOPERTA DA KAMERLINGH OHNES NEL 1911 SUL Hg, at 4.2K, LIQUEFANDO L' H_e^4.

SUL SUPERCONDUTTORE SCORRE CORRENTE SENZA CHE CI SIA D.D.P. AI SUOI CAPI, QUINDI:

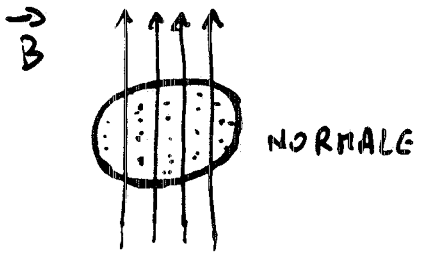
$$R \equiv 0$$

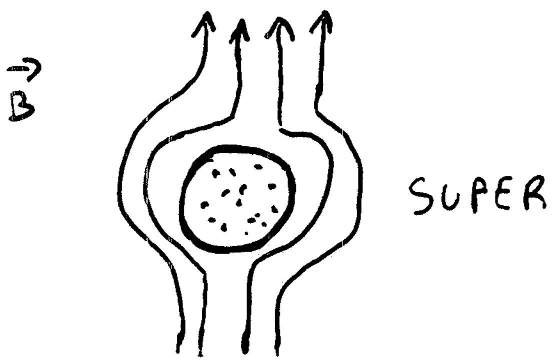


2) PERFETTO DIAMAGNETISMO.

EFFETTO MEISSNER (1935)

UN METALLO NELLO STATO SUPERCONDUTTORE NON PERMETTE LA PRESENZA DI FLUSSO DI CAMPO MAGNETICO ALL'INTERNO.





3) EFFETTO ISOTOPICO

SCOPERTO DA MAXWELL E REYNOLDS (1950)

CAMPIONI FATTI CON LO STESSO ELEMENTO MA DIFFERENTE ISOTOPO SODDISFANO ALLA RELAZIONE:

$$M^{\alpha} T_C = \text{cost}$$

CIOÈ HANNO <u>DIVERSA T_C.</u>

M = massa dell' isotopo

$\alpha \simeq 0.5$, costante

DALL'EFFETTO ISOTOPICO SEGUE:

$$\vartheta_D \cong M^{-1/2} \qquad \frac{T_C}{\vartheta_D} \simeq \text{cost}$$

QUINDI, POICHÈ ϑ_D (temperatura di Debye) è legata al reticolo, risulta che la <u>superconduttività</u> è legata al reticolo, quindi ai FONONI

4) DISCONTINUITÀ DEL CALORE SPECIFICO A $T=T_C$

Risulta che misure di calore specifico (elettronico) per $T \sim T_C$ danno:

$C_n = \gamma T$ calore specifico nello stato normale

$C_s = a \exp(-b/KT)$ calore specifico nello stato supercond.

5) ASSORBIMENTO NELL'INFRAROSSO.

I SUPERCONDUTTORI HANNO RESISTENZA NULLA IN DC E AC NON TROPPO ALTA. INOLTRE LA RIFLESSIONE E L'ASSORBIMENTO DI RADIAZIONE VISIBILE DA PARTE DI UN SUPERCONDUTTORE È LA STESSA PER $T \gtrless T_C$. POICHÈ LE PROPRIETÀ OTTICHE POSSONO ESSERE CORRELATE ATTRAVERSO LA EQ. DI MAXWELL ALLA RESISTENZA SUPERFICIALE, SEGUE CHE A FREQUENZE OTTICHE LO STATO SUPERCONDUTTORE HA LA STESSA RESISTENZA DI QUELLO NORMALE. LA REGIONE ALLA QUALE COMINCIA AD APPARIRE LA RESISTENZA CORRISPONDE ALLA REGIONE DELL'INFRAROSSO.

L'ASSORBIMENTO NELL'INFRAROSSO E LA DISCONTINUITÀ NEL CALORE SPECIFICO ELETTRONICO IMPLICANO LA PRESENZA DI UN GAP NELLO SPETTRO ENERGETICO DEGLI ELETTRONI DI CONDUZIONE.

TEORIE MICROSCOPICHE

B.C.S. (BARDEEN, COOPER, SCHRIEFFER).

PREMIO NOBEL.

PER $T < T_c$ GLI ELETTRONI SI ACCOPPIANO CON **SPIN PARALLELI** $e^- \uparrow$ $e^- \uparrow$.

È NECESSARIO UN POTENZIALE ATTRATTIVO PER VINCERE LA REPULSIONE COULOMBIANA: È FORNITO DAL RETICOLO CRISTALLINO.

ESISTE QUINDI INTERAZIONE **ELETTRONE – FONONE**.

RISULTATI DELLA B.C.S.

1) ESISTE UN GAP IN FUNZIONE DELLA TEMPERATURA $\Delta(T)$

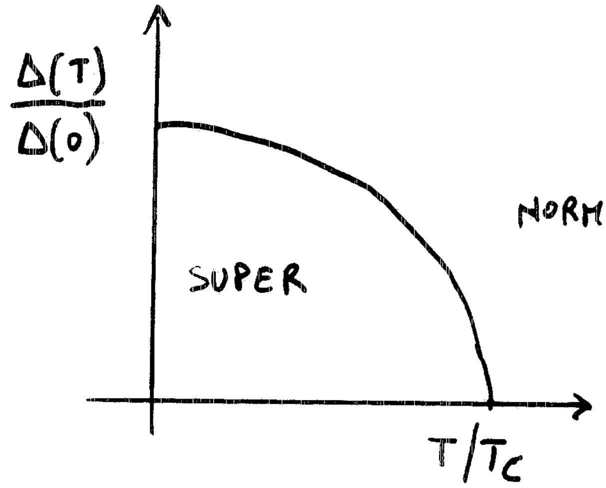
SI RICAVA INVERTENDO NUMERICAMENTE LA EQUAZIONE

$$\frac{1}{N_0(V)} = \int_0^{\hbar\omega_D} \frac{\tanh \frac{1}{2}\beta\left(E^2-\Delta^2\right)^{1/2}}{\left(E^2-\Delta^2\right)^{1/2}}\, dE$$

$N(0)$ = densità degli stati al livello di FERMI

$\beta = 1/KT$ (K = costante di Boltzmann, T = temp.)

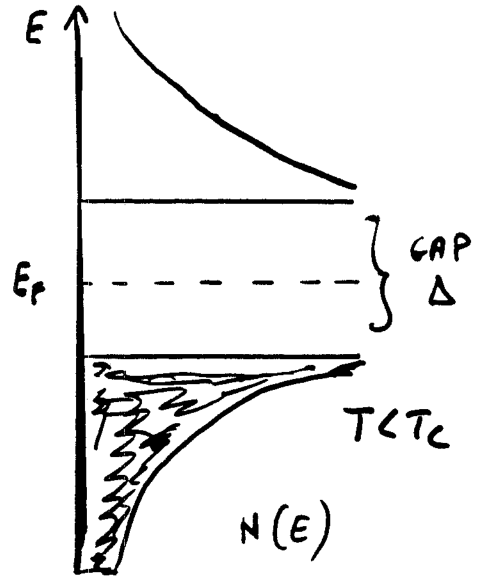
V = termine di interazione elettrone-fonone (cost.)



IN ACCORDO CON LE MISURE SPERIMENTALI

2) DENSITÀ DEGLI STATI IN FUNZIONE DELL'ENERGIA (modello a semiconduttore)

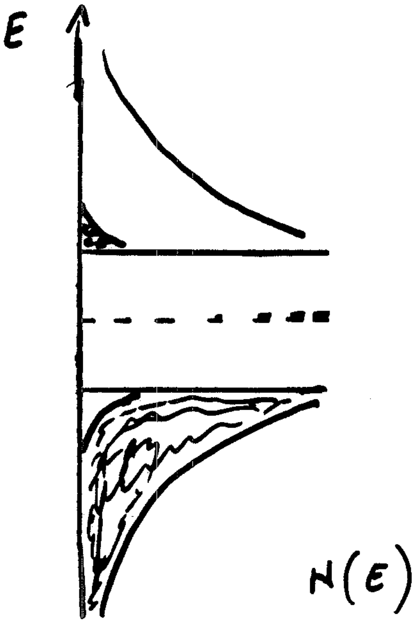
$$\frac{N_S(E)}{N_N(E)} = \begin{cases} 0 & E < \Delta \\ \dfrac{E}{\sqrt{E^2-\Delta^2}} & E > \Delta \end{cases}$$



A T=0, per $E < E_F$ TUTTI GLI STATI SONO PIENI DI ELETTRONI

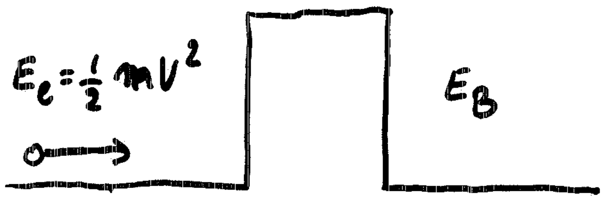
per $E > E_F$ TUTTI GLI STATI SONO VUOTI DI ELETTRONI

A $T \neq 0$ ma $< T_c$ C'È MIXING



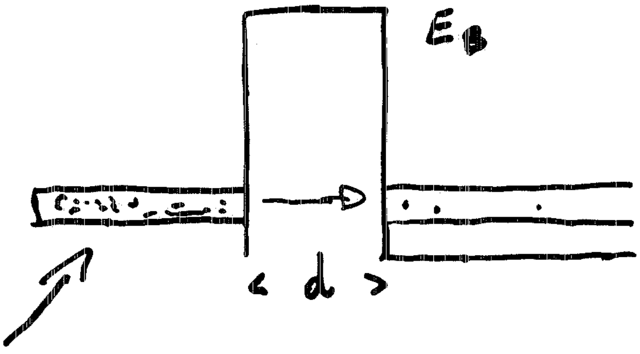
EFFETTO TUNNEL

IN MECCANICA CLASSICA UN PUNTO MATERIALE NON PUÒ OLTREPASSARE UNA BARRIERA DI POTENZIALE SE LA SUA ENERGIA RISULTA INFERIORE ALL'ALTEZZA DELLA BARRIERA STESSA.



$E_c < E_B$

IN MECCANICA QUANTISTICA (GRAZIE AL DUALISMO ONDA-CORPUSCOLO) CIÒ RISULTA POSSIBILE

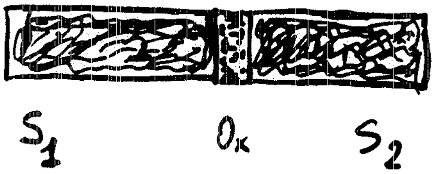


ELETTRONI CON ENERGIA MINORE DELL'ALTEZZA DELLA BARRIERA POSSONO OLTREPASSARLA ED ANDARE AD OCCUPARE GLI STATI LIBERI CORRISPONDENTI

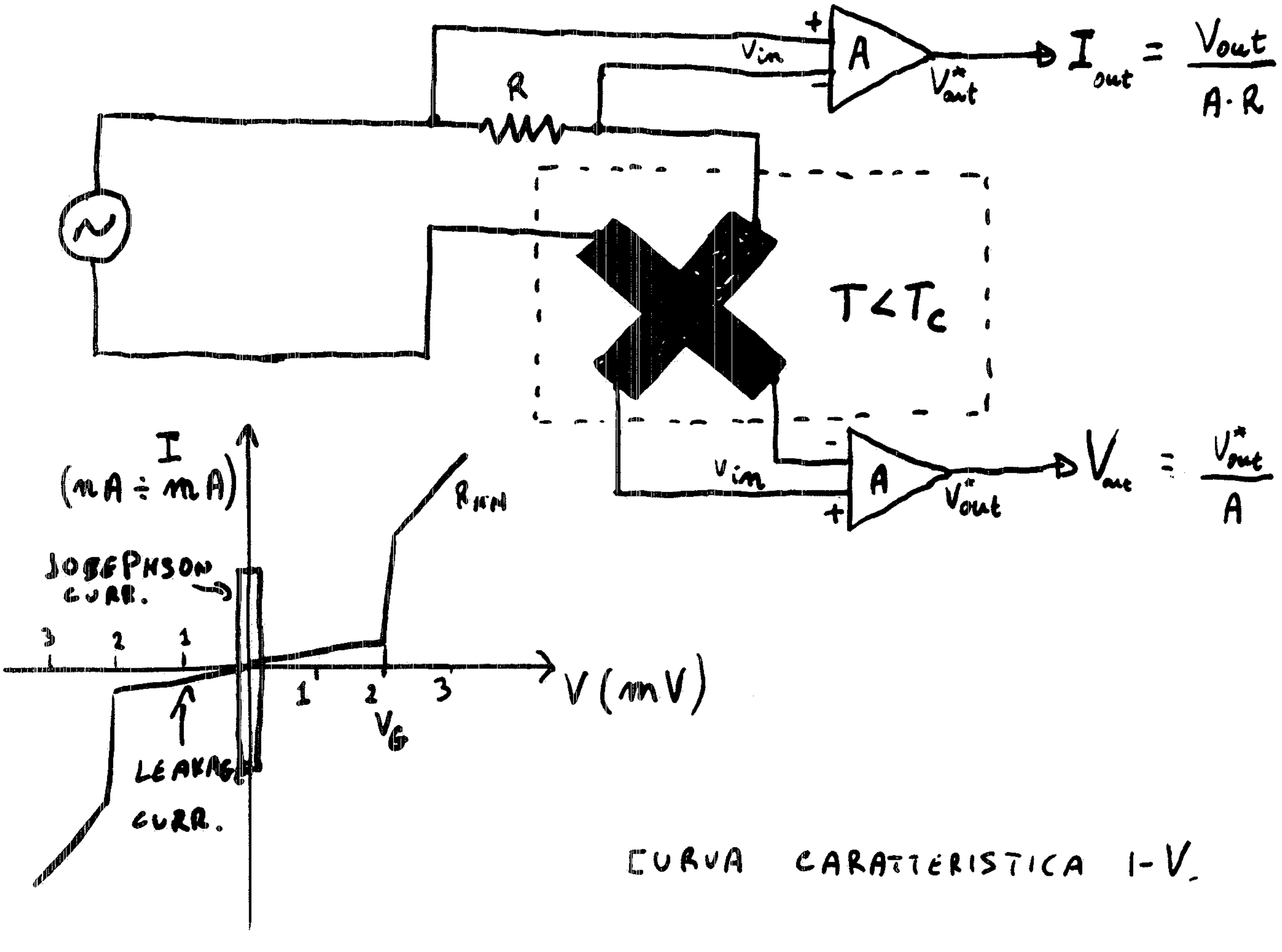
LA PROBABILITÀ DI PASSAGGIO È UNA FUNZIONE DELLO SPESSORE DELLA BARRIERA d : $p(tun) = A\, e^{-d}$

GIUNZIONI TUNNEL SUPERCONDUTTRICI

POSSONO ESSERE SCHEMATIZZATE COME LA "UNIONE" DI DUE MATERIALE SUPERCONDUTTORI S_1, S_2 CON "IN MEZZO" UN SOTTILE STRATO DI OSSIDO.



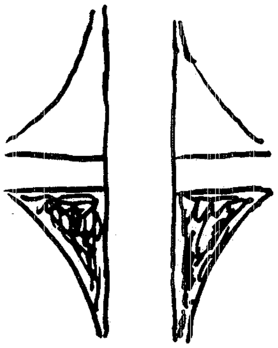
CONFIGURAZIONE SPERIMENTALE TIPICA PER I-V.



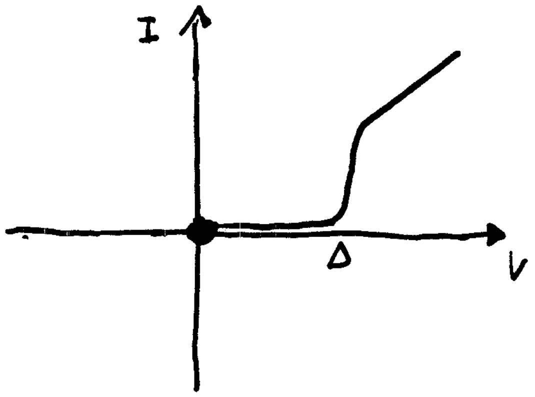
CURVA CARATTERISTICA I-V.

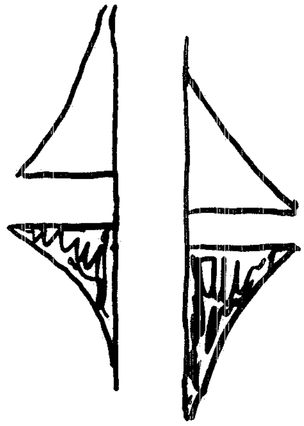
GIUNZIONI TUNNEL SUPERCONDUTTRICI: DIAGRAMMA ENERGETICO E VARIAZIONE CURVA I-V A $T=0$ PER $V=0$; $<\Delta$; $>\Delta$.

$\Delta = \Delta_1 + \Delta_2$

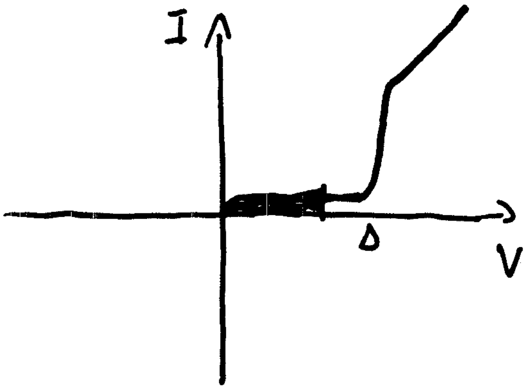


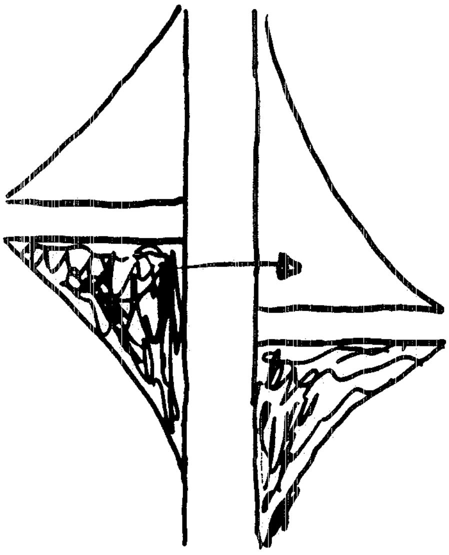
$V=0$



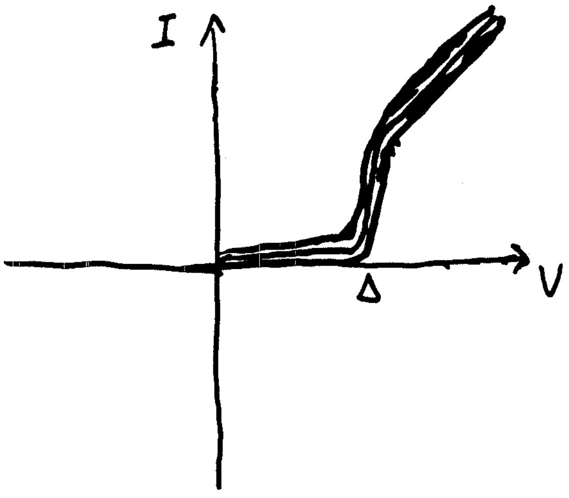


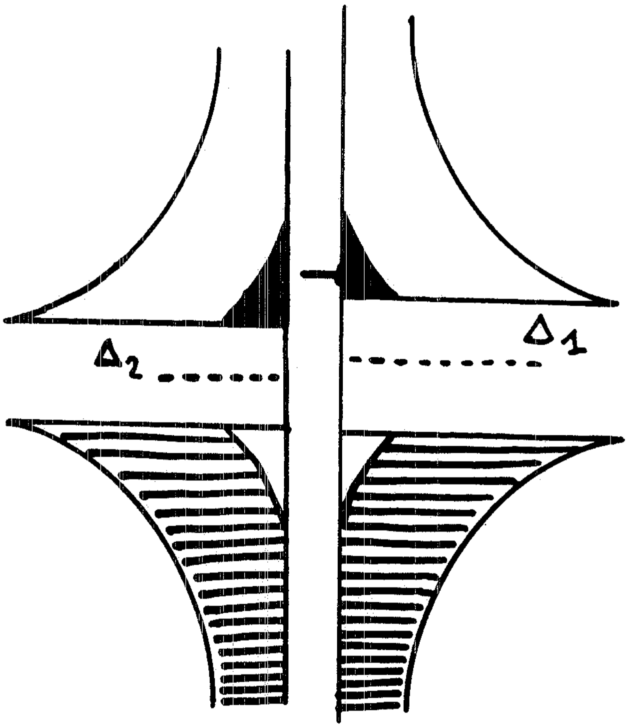
$V<\Delta$

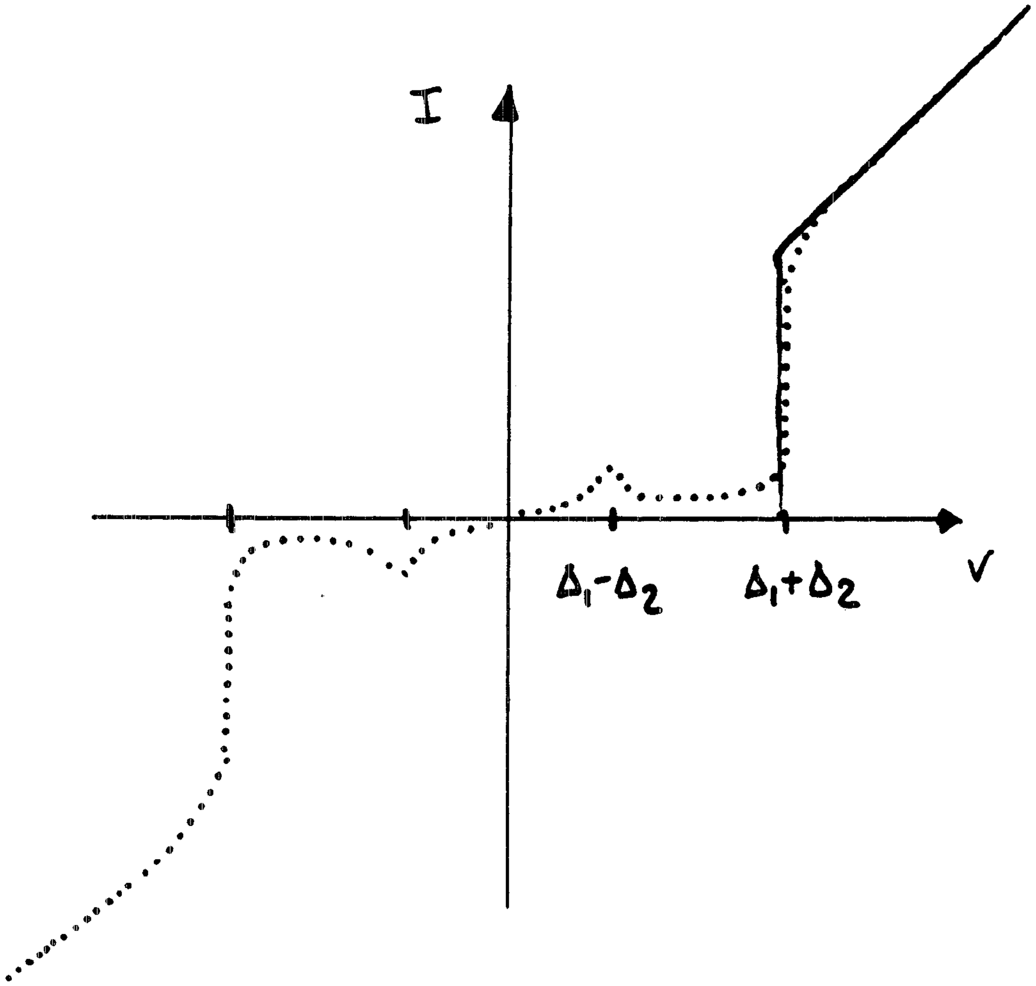




$V>\Delta$




Δ_2
Δ_1


I
V
$\Delta_1-\Delta_2$
$\Delta_1+\Delta_2$

Elemento	Tc in K	Elemento	Tc in K	Elemento	Tc in K
Al	1.18	Ti	0.39	V	5.03
Zn	0.85	Ga	1.09	Zr	0.55
Nb	9.1	Mo	0.92	Tc	11.2
Ru	0.49	Cd	0.52	In	3.41
Sn	3.72	La(β)	6	Hf	0.16
Ta	4.48	W	0.01	Re	1.7
Os	0.66	Ir	0.14	Hg(α)	4.15
Tl	2.37	Pb	7.19	Th	1.37

Tabella 1: Elementi superconduttori nel sistema periodico

T_c (K)	Binary	Ternary and higher
> 20	Nb_3Ge (23) Nb_3Ga (20.7)	$Nb_{3.16}Al_{0.64}Ge_{0.2}$ (20.7) $NbAl_{0.24}Ga_{0.06}Ge_{0.06}$ (20.4) $Nb_3Ge_{0.9}Si_{0.1}$ (20.3)
18–20	Nb_3Al (18.7) Nb_3Sn (18.3)	$Nb_3Al_{0.8}Ge_{0.2}$ (19.7) $Nb_3Al_{0.95}Be_{0.05}$ (19.6) $Nb_{0.75}Al_{0.22}Si_{0.3}$ (19.2) $Nb_3Al_{1-y}B_y$ (< 19.1) $Nb_3Al_{0.5}Ga_{0.5}$ (19) $V_3Si_{0.75}Ga_{0.25}$ (18.6)
16–18	V_3Si (16.9) NbN (16.5)	$NbN_{1-0.8}N_{1-0.8}C_{0-0.4}Ti_{0-0.4}$ (< 18) $NbN_{0.65}C_{0.35}$ (17.8) $Nb_{0.66}N_{0.85}Ti_{0.34}$ (17.6) $Nb_{1-x}N_{0.75}C_{0.25}Hf_x$ (< 17.6) $Nb_{0.998}NO_{0.002}$ (17.3) $C_{1.96}Th_{0.3}Y_{0.7}$ (17.1) $V_3Si_{1-x}B_x$ (< 17) $Cu_{8-0.85}H_{0.7}Pd_{1-0.16}$ implant (< 16.6)
14–16	Tc_3Mo (15.8) V_3Ga (15.1) MoC (14.3) $Mo_{0.57}Re_{0.43}$ (14.0)	$Ag_{8-0.4}H_xPd_{1-0.15}$ implant (< 15.6) $C_{1.95}W_{0.1}Y_{0.9}$ (14.8) $PbMo_6S_8$ (14.7) $Al_{0.5}SnMo_{5.5}S_8$ (14.4) $SnMo_6S_8$ (14.2) $C_{0.75}Hf_{0.25}Mo_{0.25}$ (14.2) $C_{1.45}La_{0.5}Th_{0.5}$ (14.2)

Tabella 2: Superconduttivita' di una selezione di composti

ESP. SLEND:

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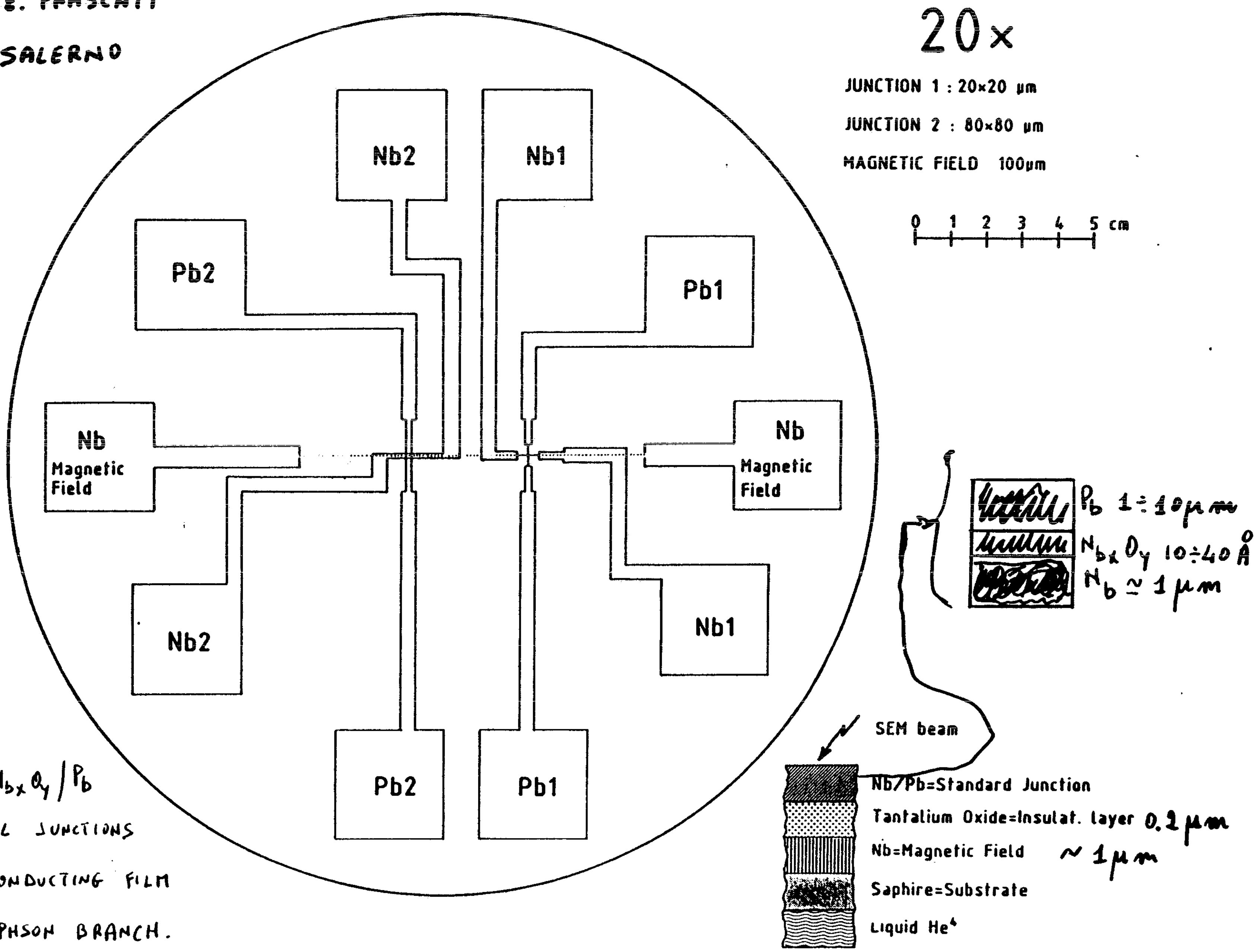


MULTISTRATE $Nb/Nb_xO_y/Pb$

JOSEPHSON - TUNNEL JUNCTIONS

PROVIDED OF SUPERCONDUCTING FILM

TO SUPPRESS JOSEPHSON BRANCH.

②

ENERGY GAP Δ^* OF CONVENTIONAL SUPERCONDUCTORS : $0.18 \div 1.5$ meV.

POTENTIALLY, IN A S.I.S. CONFIGURATION, THEY CAN BE USED AS ULTRA-HIGH ENERGETIC RESOLUTION NUCLEAR DETECTORS FOR SPECTROSCOPY PURPOSE.

IN ANY TYPE OF DETECTORS THE NUNBER N OF PRODUCED CHARGES IS, THEORETICALLY:

$$N = E_{Rel} / \varepsilon$$

where:

ε, proportional to Δ^*, is the minimal energy required to produce one free charge usefull for the detection-amplification process.

E_{rel} is the energy released in the detector itself from the ionizing particle.

③

NOMINAL ENERGETIC RESOLUTION $\Delta E / E$ OF A DETECTOR:

$$\frac{\Delta E}{E} = 2.35 \sqrt{F \frac{\varepsilon}{E}}$$

where:

F = Fano factor, experimental coefficent wich value is between 0 and 1. Typical value for semiconductor detectors: 0.35.

2.35 = Numerical factor because of Gauss distribution -

ACTUAL LOWEST VALUE OF ε FOR THE BEST OPERATING DETECTOR (SEMICONDUCTOR): 2.9 eV WITH HYPER-PURE Ge AT 77 K.

$E_{gap} = \Delta^*$ of Ge at 77K is $\approx$ 0.9 eV.

MATERIAL	ε (eV)	T (K)
PLASTIC SCINTILL.	100	300
GAS DETECT.	20 ÷ 100	300
NaI	25	300
Si SEMICONDUCT.	3.6	300
Ge SEMICONDUCT.	2.9	77
HIGH TC SUPERCONDUCTOR	0.025	90
CONVENTIONAL SUPERCONDUCTOR	0.001	4.2

BECAUSE $\Delta E/E$ IS JUST PROPORTIONAL TO $\sqrt{E}$, SUPPOSING THE SAME VALUE FOR F, IT IS POSSIBLE TO DEVELOP A SUPER-DETECTOR THAT WORKS 30÷50 TIMES BETTER THAN Ge JUST USING SUPERCONDUCTING TUNNEL JUNCTIONS (STj) IN THE GIAEVER REGIME.

UNFORTUNATELLY, IT IS NOT A SIMPLE JOB!!

Tab. I - Experimental results and operating conditions for the experiments performed with STJ as nuclear detector.

Authors	Wood, White	Kurakado	Barone	Barone	Barone	Tweren-bold
Year	1973	1983	1985	1985	1985	1986
Junction type and geometry	Sn-SnO-Sn cross	Sn-SnO-Sn cross	Nb-NbO-Pb cross	Nb-NbO-Pb island	Nb-NbO-Pb cross	Sn-SnO-Sn cross
Film thickness (Å)	2000; 1000	1500; 1500	2900; 35000	1000; 20000	1000; 20000	1500; 6500
Oxide thickness (Å)	10	20	10	10	10	10
Overlap (cm^2)	7.10^{-4}	$1.10.3^{-3}$	1.10^{-4}	1.10^{-4}	1.10^{-4}	1.10^{-4}
Temp. (K)	1.2	0.32	1.4	1.4	1.4	0.36
Source	^{239}Pu; α	^{210}Po; α	^{241}Am; α	^{241}Am; α	^{241}Am; α	^{55}Fe; X
$E_{rel.}$ (keV)	500	70	900	3800	3800	5.89
Preamp.	current.	charge	voltage	voltage	voltage	charge
Cable leng.(m)	—	1.5	0.6	0.6	0.6	0.4
ε(eV),exp.	0.141	—	0.07	0.18	0.25	0.003
ΔE/E,exp.(%)	—	6.9	37	22	31	0.7
R_{NN} (mΩ)	77	—	20	1÷2	1÷2	470
R_d (Ω)	10	—	—	—	—	100k
C_d(pF)	9000	—	—	—	—	500

⑥

WE CONSIDER:

STJ COUPLED TO A VOLTAGE OR CHARGE AMPLIFIER.

WE SUPPOSE:

a) IDEAL JUNCTIONS, i.e. WITHOUT TRUE LEAKAGE CURRENTS

b) THE JUNCTION UNIFORMELY PERTURBED BY THE IONIZING PARTICLE

c) IDEAL AMPLIFIERS

WE ANALYSE:

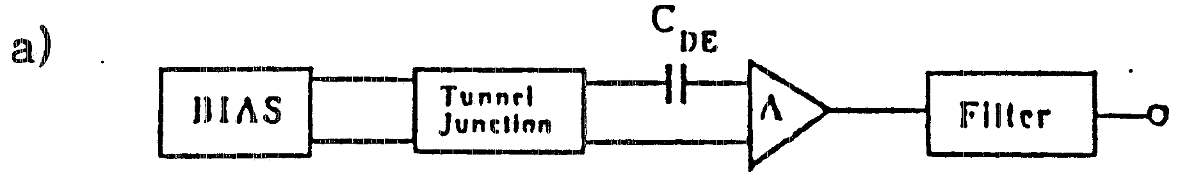
THE SIGNAL TO NOISE RATIO AS A FUNCTION OF:

a) THE TEMPERATURE T

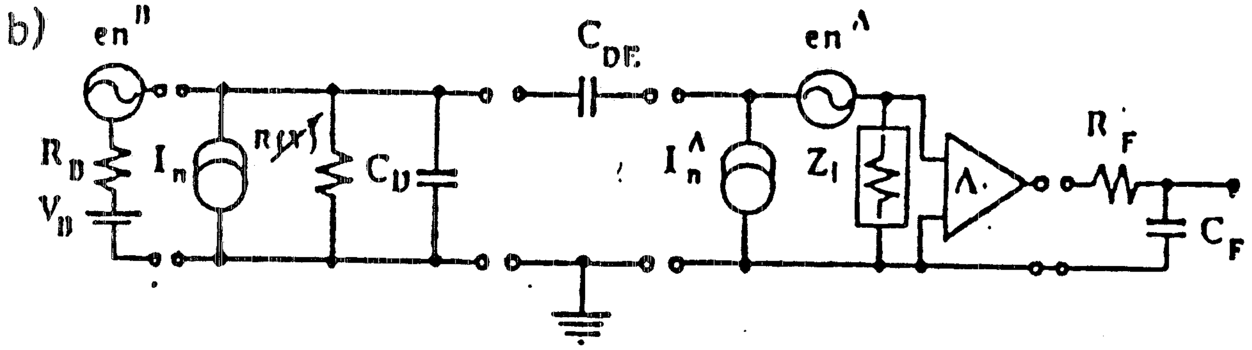
b) THE TUNNEL PROBABILITY p.

STJ DETECTION SYSTEM

We analyze the STJ connected to a bias network and a preamplifier followed by a optional filter.



EQUIVALENT CIRCUIT OF STJ:



The R(V)^D resistance of STJ changes because impinging perticle and generetes the signal.

CHARACTERISTICS TIMES

The detection system is characterized by four characteristic times as following:

1) DETECTOR TIME $\tau_D = C_D R_D = \tau_D(\rho, T)$

2) TUNNEL TIME $\tau_t = 1/\rho$

3) RECOMBINATION TIME $\tau_r(T)$

4) FILTER TIME τ_F

DETECTOR TIME

The detector time is the product of detector resistance R_D for the detector capacitance C_D.

C_D is very large: the intrinsic value is of the order of $30 \mu F/cm^2$ because very thin (~ 10 Å) oxide thickness of STJ.

TUNNEL TIME.

The tunnel time τ_t is the "middle" transit time of the excess quasiparticles, generated by the excitation, causing the charge collection process.
It is given by:

$$\tau_t = R_{NN} e^2 N_0 A d \qquad (1)$$

where:

R_{NN} = normal state resistance at $V \gg (\Delta_1 + \Delta_2)/e$

e = electron charge

N_0 = density of states at Fermi energy level

A = junction area

d = thickness of the film.

TYPICAL ORDER OF MAGNITUDE:

$$\tau_t = 2\,\mathrm{ns}\; R_{NN}(\Omega)\, A(\mu m^2)\, d(\mu m)$$

for P_b, N_b, S_n, between ± 30%

RECOMBINATION TIME.

The recombination time τ_r is the "middle time" of quasiparticle recombination.

It limits the charge collection and in a quasi-equilibrium state can be approximated by:

$$\tau_r = \tau_0 \, e^{(\Delta^*/K_B T)} \Big/ \sqrt{\pi \frac{T}{T_c}} \cdot \left(2\Delta^*/K_B T_c\right) \qquad ②$$

where:

τ_0 = characteristic quasi particle time; depends on material

T_c = transition (or critical) temperature; depends on material.

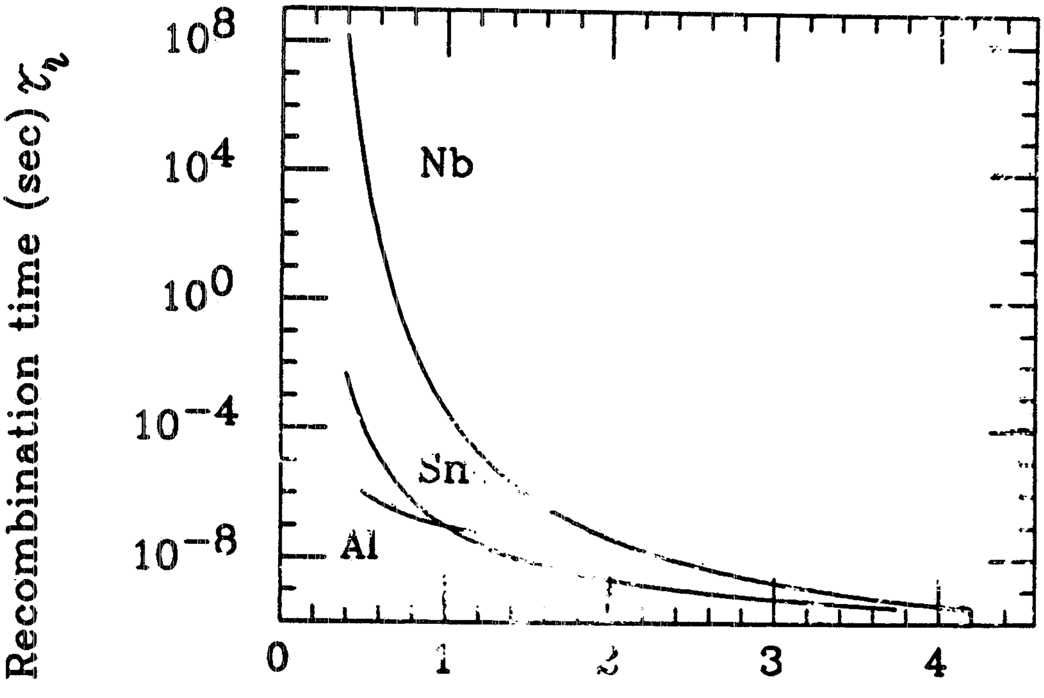


FIG 2. Temperature dependance of the recombination time for Al, Sn, Nb. Numerical values from eq 2.

FILTER TIME

About the filter, in this paper we consider only a low-pass filter with a characteristic time τ_F wich determines the upper limit of the bandwidth (BW) of the amplifier.

In a first analysis τ_F can be taken equal to τ_R that is the effective quasiparticle relaxation time.

In this way we have:

$$BW = 1/\tau_R = 1/\tau_r + 1/\tau_t \quad ③$$

As a consequence, the characteristic detector time $\tau_D = C_D R_D$ can be comparable with the signal time τ_r and τ_t.

Comparing eq 1 and eq 2 it is shown that the condition:

$$\tau_R \gg \tau_t$$

usual for conventional detectors, is satisfied only when R_{NN} or T are low.

⑬

EQUIVALENT CIRCUIT OF STJ

Under the hypothesis of:

1) No true leakage currents in STJ

2) "Low value" of p, i.e. $\tau_t \gg \tau_r$

the tunnel current, in the unperturbed state, has the following expression:

$$I = f(V,T)/R_{NN} = g(V,T)\,p \qquad (4)$$

Following eq 1 we obtain that

a) R_{NN}

b) $R_s = V/I = 1/G_s$ the static resistance

c) $R_d = dV/dI = 1/G_D$ the dynamic resistance

are all inversely proportional to the tunnel probability $p = 1/\tau_t$ and the functions

$$f(V,T) \quad ; \quad g(V,T)$$

depend on the junction electrodes.

EQUIVALENT CIRCUIT OF STJ

⑭

When the ionizing particle hits the junctions the quasi-static I-V characteristic is:

$$I' = g'\left(V, T, n'(E, t)\right) \cdot p \qquad (5)$$

where:

$n'(E,t)$ = time dependence of the energy distribution of the excess quasiparticle with energy E.

In a first approximation we can neglect the details of the energy distribution and the current I' is only a function of the total number of quasi particles:

$$n'(t) = \int_0^\infty n'(E,t)\, dE$$

IF:

THERMAL QUASIPARTICLE CURRENT IS INDEPENDENT OF EXCESS QUASIPARTICLE CURRENT (voltage bias)

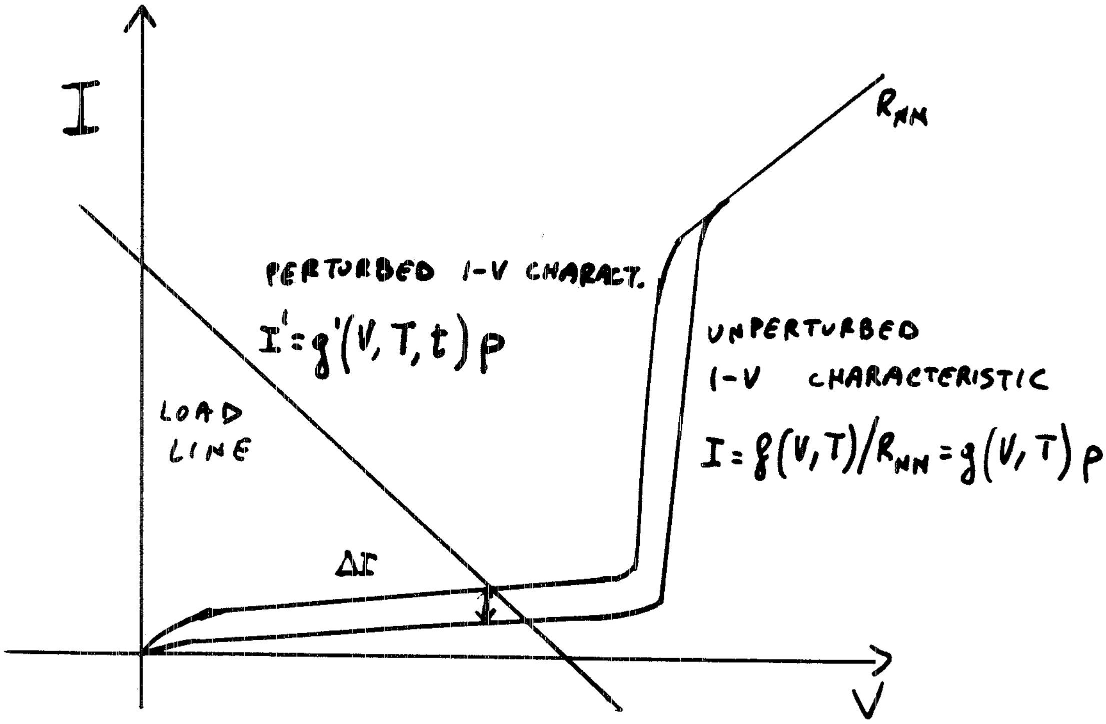
FOR

$$0 \leq V \leq \Delta_1^* + \Delta_2^*$$

the signal current $\Delta I = I' - I$ can be approximated by:

$$\Delta I = p\, n'(0)\, e^{(-t/\tau_R)} = \Delta I_0\, e^{-(t/\tau_R)} \qquad (6)$$

14a



$$\Delta I = \rho n'(0)\, e^{-t/\tau_R} = \Delta I_0\, e^{-t/\tau_R} \qquad (6)$$

$$1/\tau_R = 1/\tau_t + 1/\tau_\eta$$

EQUIVALENT CIRCUIT OF STJ

Following eq 6, we have:

The excess current is proportional to ρ, i.e. to the inverse of the resistence.

In eq6 we have neglected:

1) GAP REDUCTION caused by the excess quasiparticle;

2) Some others "exotic" phenomena that can enable moltiplication or "avalanche like" processes.

Under these semplifications and approximations the equivalent circuit of STJ is:

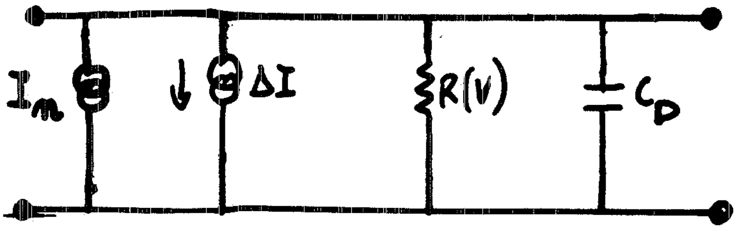


Fig 3: EQUIVALENT CIRCUIT OF THE STJ

COMMENTS TO THE EQUIVALENT CIRCUIT OF STJ.

(16)

Due to the presence of:

a) bias network

b) amplifier

the effective current or voltage signals are strictly related to the intersection of the load line with the perturbed and the unperturbed I-V characteristics.

DYNAMIC CONDITIONS

The true dynamic load line must be considered, taking into account the effects of:

a) cables

b) input impedance of the amplifier

c) junction self-capacitance

d) some impedence matching network if necessary-

VOLTAGE SIGNAL

From the model of Fig 3, the signal voltage measured with a voltage amplifier is maximized by a current polarization and has the following expression:

$$\Delta V = R_D \Delta I_0 \left(e^{-t/\tau_R} - e^{-t/\tau_D} \right) \cdot \left(1 - \tau_D/\tau_R \right) \qquad (7)$$

From eq 7 it follows:

1) For low value of ρ, i.e. for R_D enough large so get $\tau_D \gg \tau_R$, the detector time τ_D cuts the voltage signal.

2) As ρ increases the dynamic resistance decreases; as we get $\tau_D < \tau_R$ the capacitor effects can be neglected and the voltage signal becomes:

$$\Delta V = \Delta I \, R_d \qquad (8)$$

3) The maximum voltage signal $V(t)$ is:

$$\Delta V(t^*) = R_D \Delta I_D \left(\frac{\tau_R}{\tau_D} \right)^{\tau_D/(\tau_D - \tau_R)} \qquad (9)$$

VOLTAGE SIGNAL (18)

IN THE LIMIT OF $\tau_D \to \infty$ (i.e. for $\tau_D \gg \tau_R$) we get:

$$\Delta V(t^*) = \frac{\Delta I_0}{C_D}\,\tau_R \qquad (10)$$

IN THE LIMIT OF $\tau_D \to 0$ we get:

$$\Delta V(t^*) = R_D\,\Delta I_0 \qquad (11)$$

VOLTAGE NOISE (19)

The spectral distributione of the CURRENT NOISE in a STJ is:

$$I_n^2(\omega) = (e/\pi)\, I(V)\, \mathrm{cotgh}(eV/2k_B T) \qquad (12)$$

wich can be written as:

$$I_n^2(\omega) = F(V,T)/(\pi R_S) \qquad (13)$$

where

1) $F(V,T) = eV$ if $eV/k_B T \gg 1$ SHOTKY NOISE

OR

1') $F(V,T) = 2K_B T$ if $eV|K_B T \ll 1$ JOHNSON NOISE (from R_S)

The spectral density of VOLTAGE NOISE is:

$$V_n^2(\omega) = I_n^2(\omega) R_D^2 = \frac{F(V,T)}{\pi R_S} R_D^2 \qquad (14)$$

FROM EQ (13) and EQ (14) it results that $V_n^2(\omega)$ is proportional to $1/\rho$.

VOLTAGE NOISE ⑳

THE S/N ratio is given combining eq (9), (13), (14) and we will get:

$$S/N = \Delta I_0 \frac{R_s \pi}{\sqrt{F(V,T)}} \left[\left(\frac{\tau_R}{\tau_D} \right)^{\tau_D/(\tau_D - \tau_R)} \right] \cdot \sqrt{\tau_R} \qquad (15)$$

a) IF $\tau_D \to 0$ we have:

$$S/N = p\, n'(0) \frac{\sqrt{\pi} R_S}{\sqrt{F(V,T)}} \cdot \tau_R^{1/2} \qquad (16)$$

b) IF $\tau_D \to \infty$ we have:

$$S/N = \frac{p\, n'(0)}{C_D R_D} \frac{\sqrt{\pi} R_S}{\sqrt{F(V,T)}} \cdot (\tau_R)^{3/2} \qquad (17)$$

DISCUSSION ON S/N VERSUS p and T

(VOLTAGE NOISE) ㉑

1) At a fixed T value, starting from low values of p, by eq(17) the S/N INCREASES with p, then:

OPTIMUM CONDITIONS ARE OUT OF THE HIGH τ_D LIMIT.

2) Following eq 16 we have:

S/N INCREASES WITH P BUT IT SATURATES AS $\tau_t > \tau_n$

3) At a fixed p value, as T decreases, following eq(16):

S/N DECREASES BUT AFTER IT SATURATES.

3a) MOREOVER, AS R_D INCREASES we will go in the high τ_D limit and, by eq(17);

S/N DECREASES WITH THE TEMPERATURE DECREASING.

CHARGE AMPLIFIER

For a charge amplifier coupled to STJ the DYNAMIC LOAD LINE is determined by the LOW VALUE of INPUT IMPEDANCE of AMPLIFIER.

1) CURRENT SIGNAL optimized for a VOLTAGE DYNAMIC POLARIZATION, i.e. for a DYNAMIC LOAD $R_L^D \ll R_D$.

2) DETECTOR PLUS BIAS NETWORK MUST BE A CURRENT SOURCE IN COMPARISON WITH THE AMPLIFIER. Then:

$$R_B > R_S(V) \gg |Z_i|$$

By integration of eq (6) the charge signal is:

$$\Delta Q = p\, n'(0)\, \tau_R \tag{18}$$

Then, as p increases, we have:

a) ΔQ at the beginning is PROPORTIONAL to p;

b) As $\tau_t < \tau_r$,

ΔQ saturates to the limit value: $\Delta Q = n'(0)$.

Moreover, by eq (13), the spectral density of the current noise INCREASES INDEFINITELY with the INCREASE OF p.

Then the S/N ratio is:

$$\frac{S}{N} = p\, n'(0)\, \tau_R \sqrt{\frac{\pi R_s}{F(V,T)\, BW}} = p\, n'(0) \sqrt{\frac{\pi R_s}{F(V,T)}}\; \tau_R^{3/2} \qquad (19)$$

1) THE MAXIMUM VALUE OF S/N IS FOR:

$$p = 1/2\tau_R$$

2) By substitution in eq 18, for $eV/k_BT \gg 1$ we obtein:

$$\left(\frac{S}{N}\right)_{MAX} = n'(0)\left[2\tau_R\, \pi/(e I)\right]^{1/2} / 3^{3/2} \qquad (20)$$

3) In the limit $eV/k_BT \ll 1$ we obtein:

$$\left(\frac{S}{N}\right)_{MAX} = n'(0)\left[\tau_2\, \pi R_s/k_B T\right]^{1/2} / 3^{3/2} \qquad (21)$$

COMMENT: IN THE TWO LIMITS THE S/N RATIO INCREASES RESPECTIVELY BY DECREASING THE CURRENT BIAS VALUE AND BY INCREASING THE VALUE OF THE STATIC RESISTANCE OF THE WORKING POINT.

DISCUSSION OF S/N VERSUS T

In the case of CHARGE AMPLIFIER COUPLED TO STJ THE CHARACTERISTIC DETECTOR TIME τ_D DOESN'T PLAY ANY ROLE.

AS A CONSEQUENCE, WITH THE DECREASING OF T WE GET:

1) INCREASING OF THE SIGNAL, WHICH SATURATES TO ITS LIMIT VALUE $\Delta Q = n'(0)$;

2) A DECREASING OF THE SPECTRAL DENSITY OF THE CURRENT NOISE;

3) A DECREASING OF THE BW, WHICH SATURATES TO ITS LIMIT VALUE $1/\tau_t$.

THE RESULT, FOLLOWING Eq 19, IS:

THE SIGNAL TO NOISE RATIO INCREASES INDEFINITELY WITH THE DECREASING OF THE TEMPERATURE_

CONCLUSIONS

We have supposed IDEAL STJ, without true leakage currents, PERTURBED IN A UNIFORM WAY by a ionizing particle, COUPLED TO A NOISELESS BIAS NETWORK and to NOISELESS IDEAL VOLTAGE or CHARGE AMPLIFIER

By using a VOLTAGE AMPLIFIER the S/N has the following behaviour:

1) S/N INCREASES AS p INCREASES BUT IT SATURATES;
2) S/N SHOWS A MAXIMUM WITH THE DECREASE OF T.

By using a CHARGE AMPLIFIER we have:

1) S/N SHOWS A MAXIMUM AS A FUNCTION OF p
2) S/N INCREASES INDEFINITELY AS THE TEMPERATURE DECREASES_

FURTHER DEVELOPMENTS AND ANALYSIS

IT IS NECESARY TO TAKE INTO CONSIDERATIONS:

1) EFFECTS OF NON-IDEAL AMPLIFIERS (BW, NOISE, Z_{in}).

2) THE "IDEAL" OPTIMIZATION OF S/N LEADS TO RECOMBINATION TIMES LONGER OR OF THE SAME ORDER OF MAGNITUDE OF THE TUNNEL TIME. WE MUST REMEMBER THAT:

2a) IN THE CONDITION $\tau_t \ll \tau_2$ (IN WHICH IS VALID THE USUAL LOWEST ORDER PERTURBATIVE ANALYSIS OF THE TUNNEL CURRENT) THE TUNNEL PROCESS DOESN'T CHANGE THE EQUILIBRIUM STATE OF THE TWO FILMS;

2b) IF $\tau_t \gg \tau_2$ THE TUNNEL ITSELF PERTURBS THE THERMAL EQUILIBRIUM IN THE SUPERCONDUCTING FILMS. IN THIS LIMIT SOME ANOMALIES IN THE I-V CHARACTERISTICS SHOULD BE OBSERVED AND A HIGHER ORDER PERTURBATIVE ANALYSIS SHOULD BE DONE, SO THAT THE USUAL SEMICONDUCTING MODEL COULD NOT BE STILL VALID.

3) AT THE ARRIVAL OF THE IONIZING PARTICLE ONLY A SMALL PORTION OF THE JUNCTION IS STRONGLY EXCITED AND THE INFLUENCE OF SUCH VARIATION ON THE GLOBAL CURRENT VOLTAGE (I-V) CHARACTERISTIC SHOULD BE TAKEN INTO ACCOUNT.

4) About the time and spatial evolution of the perturbed state, the usual non-equilibrium theory has been developed for systems near the equilibrium, homogeneous in the space and not explicitly time dependent. The experimental condition of a STJ under the excitation of a nuclear particle is quite different and just opposite to the three previous items: a state very far from the equilibrium is generated in a very limited spatial region. Later on, the quasiparticle diffuse in the surrounding film generating a smaller perturbation into a larger one. Moreover, other excitations such as SURFACE PLASMONS could play some role in the diffusion process.

In particular it should be analysed:

4a) The recombination time for a superconducting state far from the equilibrium

4b) Quasi-particle diffusion dynamics

4c) Effects of space inhomogeneity on the effective quasi-particle recombination time

5) Effects of the presence of disuniformities in the STJ and of true leakage currents on the experimental value of intrinsic resolution.

CONCLUSIONI SULLE PROBLEMATICHE E PROSPETTIVE ALLA LUCE DEGLI ULTIMI RISULTATI TEORICI E SPERIMENTALI.

1) IL RIVELATORE A GIUNZIONE TUNNEL SUPERCONDUTTRICE È UNA REALTÀ O MEGLIO UNA NECESSITÀ PER APPLICAZIONI PARTICOLARMENTE "SPINTE" DOVUTE AD ESIGENZE DI ALTA RISOLUZIONE ENERGETICA E/O SPAZIALE ED ALTI RATES DI CONTEGGIO.

2) LA ANALISI TEORICA DEL COMPORTAMENTO GIUNZIONE-ELETTRONICA FRONT END, COME QUELLA DA NOI SVILUPPATA, PORTA A VALORI NUMERICI INTERESSANTI E SOPRATTUTTO NON TROPPO DISTANTI DALLE ATTUALI POSSIBILITÀ DELLA TECNOLOGIA (MOLTI DEI SI JFET "LAVORANO" BENE AL LN_2, IL NOSTRO GRUPPO HA "TROVATO" DEGLI ECONOMICI GaAs MESFET CHE FUNZIONANO MOLTO BENE SIA AL LN_2 CHE AL LHe^4).

3) LA RECENTE RIVOLUZIONARIA SCOPERTA DI SUPERCONDUTTORI AD ALTA TEMPERATURA CRITICA, ~ 90K, P.E. $Y_1 Ba_2 Cu_3 O_{7-\delta}$, E LE MISURE EFFETTUATE SUL VALORE DEL LORO GAP (≃ 25 meV) FANNO NASCERE REALISTICHE SPERANZE DI POTER OTTENERE, AI TEMPI NON TROPPO LUNGHI (VISTI GLI INTERESSI ECONOMICI, SCIENTIFICI E PURTROPPO ANCHE STRATEGICI IN GIOCO) UN "FACILE" RIVELATORE CHE PUR LAVORANDO ALLA ALTA ED ECONOMICA TEMPERATURA DELL'LN_2 (COSTO DI 1 LITRO DI AZOTO LIQUIDO ≪ 1 LITRO ACQUA DI FIUGGI...) HA UNA POTENZIALE RISOLUZIONE ENERGETICA CHE È ~ 8 VOLTE MIGLIORE DEL MIGLIORE RIVELATORE AL Ge ATTUALMENTE ESISTENTE,

QUINDI

VENITE CON NOI, SUPERCONDUTTORE È BELLO, QUELLO AD ALTA T_C È ANCHE FACILE....