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Munich Cryogenic Detector Development 1995

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At the Technical University of Munich and the Max Planck Institute of Physics we are developing cryogenic detectors for the detection of small deposited energies, for example from the elastic scattering of WIMP dark matter particles, or the absorption of X-rays. Together with the University of Oxford and the Laboratori Nazionali del Gran Sasso we are preparing the CRESST experiment which uses our detectors to search for WIMP dark matter. This preprint contains reports of our work which we have presented at the Sixth International Workshop on Low Temperature Detectors (LTD-6) in Beatenburg/Interlaken, Switzerland, 28 Aug. - 1 Sept. 1995. This work has been supported in part by the "Sonderforschungsbereich 375 für Astroteilchenphysik" and the EU ERBCHRXCT930341 Network on Cryogenic Detectors.

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Measurement of the tunnel rate in S-I-S' tunnel junctions as function of bias voltage

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Abstract

Cryogenic detectors with superconducting tunnel junctions can provide an energy resolution improved by at least one order of magnitude compared with standard semiconductor detectors. While the detection principle was already demonstrated many years ago, the past years were dedicated to the transition from the laboratory sample to practical detectors. Our most favoured detector design gives rise to tunnel junctions with electrodes of unequal energy gaps. In such hetero tunnel junctions bias conditions can be established which cause a negative signal current. We report the experimental verification of this effect and we discuss the yield of charge signal of cryogenic detectors based upon superconducting tunnel junctions.

1 Introduction

Superconducting tunnel junctions are used in a very wide field of applications. One of these applications are cryogenic detectors for particle and astrophysics [1],[2]. After initial experiments which demonstrated the feasibility of the detection scheme it was necessary to transform the devices from laboratory samples to reliable detectors [3]. The most commonly used detector design gives rise to tunnel junctions with electrodes of unequal energy gaps which causes the phenomenon discussed in this paper.

A superconducting tunnel junction consists of two metal films which are separated by a thin tunnel barrier. Superconducting materials exhibit an energy gap in the excitation spectrum of single electrons when cooled below a material-specific critical temperature T_C . Below T_C , the electrons which occupied the energy range within the gap condense to Cooper pairs. Energy deposition in the tunnel junction causes the creation of quasiparticles by breaking of Cooper pairs. These quasiparticles, in excess to those already thermally excited, cause an excess tunnel current. We operate our tunnel junctions at a temperature of less than $1/10$ of T_C in order to avoid thermally excited quasiparticles as much as possible. Then, the excess tunnel current is roughly proportional to the density of excited quasiparticles. The proportionality constant γ_T however, contains all details of the tunnel process and is also a function of bias voltage. We will show that γ_T may become zero or even negative.

Detectors based upon silicon have indeed reached their maximum resolving power and a significant improvement is only possible by reducing the amount of energy required to create one charge carrier. Since the energy gap in superconducting materials is smaller by more than three orders of magnitude compared with standard semiconductor detector materials, superconductors appear suitable for this purpose. Although superconducting tunnel junction detectors produce more charge than semiconductor devices for an equal amount of deposited energy, the electronic noise charge associated with these detectors reduces their advantage somewhat. Meanwhile, we have electronics available which were designed to match the properties of our tunnel junctions with regard to optimal signal to noise ratio. Provided the full charge produced in the detector is measured, the fluctuations of the signal introduced by electronics should be comparable to those caused by the statistics of the quasiparticle creation. It should be possible to improve the energy resolution for X-ray detectors from presently $\Delta E = 119 \text{ eV}$ (FWHM) at 5.89 keV for semiconductor devices to less than 6 eV by using superconducting tunnel junctions. At present, however, quite often less charge signal than expected is actually detected. One reason for this reduced signal arises from the tunnelling processes possible in superconducting tunnel junctions with electrodes of unequal energy gaps. In our most favoured detector design, the tunnel junction electrodes are both made of aluminium, but due to the proximity effect the energy gaps are modified (see fig. 1). The aluminium tunnel junctions in earlier experiments had no additional layers attached. Thus, the electrodes of these tunnel junctions exhibited equal energy gaps Δ for both electrodes. The tunnel rate constants were calculated for small excess densities of quasiparticles and for low operating temperatures ($T \rightarrow 0$). These constants exhibit only a simple dependence on bias voltage V_B , and the signal of the detector has always a unique polarity. The tunnel rate constants for tunnelling from left to right γ_{TL} and reverse γ_{TR} are given by [5]:

$$\gamma_{T_{L,R}} = \frac{1}{4e^2 N_N R_{NN} A d_{L,R}} \cdot \frac{\Delta + eV_B}{\sqrt{(\Delta + eV_B)^2 - \Delta^2}} \quad (1)$$

N_N , R_{NN} , A , and $d_{L,R}$ are the single spin density of states in the normal conducting state at the Fermi level, the resistance of the tunnel junction for voltages $V \gg 2\Delta/e$, the

Figure 1: Geometry of the entire detector (a: cross section, b: top view) and the levels of the superconducting energy gaps (c: entire detector, d: situation underneath one tunnel junction). Diagram c shows quasiparticle propagation after creation by X-ray absorption and how they get trapped by the tunnel junctions. In this paper we consider only energy absorption in the proximity layer underneath one of the tunnel junctions (STJ). Due to the higher energy gap of the surrounding Ta absorber, quasiparticles created by energy absorption within the proximity layer are confined there. In the text we assume $\Delta_l = \Delta_{Prox}$ and $\Delta_r = \Delta_{Al}$.

area across which tunnelling is possible and the thickness of the electrode from which the tunnel process originates, respectively. The entire detector geometry is shown in fig. 1. A superconducting thin film of tantalum acts as absorber for X-rays. Quasiparticles created therein propagate by diffusion to the attached aluminium tunnel junctions where they get trapped due to the lower energy gap of the tunnel junction material. The details pertaining to quasiparticle trapping and the detector itself have been published elsewhere [3]. Here, we will discuss the charge yield which is measured by the amount of electrical charge crossing the tunnel barrier. The yield is a measure which describes the efficiency of the tunnel junction for converting excess quasiparticles in the left layer (cf. fig. 2) into a charge signal.

Figure 2: Tunnel processes in tunnel junctions of electrodes with unequal energy gaps. The figure shows the densities of states normalized to the normalconducting density of states for the left and the right layers g_l and g_r as a function of energy. The bias voltage V_B in the upper diagram is $V_B < (\Delta_l - \Delta_r)/e$ and in the lower diagram $V_B > (\Delta_l - \Delta_r)/e$. The different tunnel processes and their occurrences are discussed in the text and compiled in table 1.

2 Tunnel Processes in Heterostructures

In tunnel junctions with electrodes of unequal energy gaps an important consequence for detector applications is that the tunnel rate constant may be much smaller than expected. This could also explain a reduced signal charge in X-ray detectors based upon superconducting tunnel junctions.

We will now discuss the different tunnel processes which can occur in tunnel junctions with materials of equal energy gaps for both electrodes ($\Delta_l = \Delta_r$) and those with unequal energy gaps ($\Delta_l \neq \Delta_r$). Figure 2 shows the various tunnel processes. The left layer of the tunnel junction is connected to electrical ground. Thus, increasing bias voltage corre-

Pcs.	process allowed	process possible in case $\epsilon_l = \Delta_l$ and $\epsilon_r = \Delta_r$	quasiparticle current	electron current
1	$\epsilon_l \geq \Delta_r - eV_B$	$V_B \geq (\Delta_r - \Delta_l)/e$ (always)	$\Rightarrow$	$\Rightarrow$
2	$\epsilon_l \geq \Delta_r + eV_B$	$V_B \leq (\Delta_l - \Delta_r)/e$	$\Rightarrow$	$\Leftarrow$
3	$\epsilon_r \geq \Delta_l + eV_B$	$V_B \leq (\Delta_r - \Delta_l)/e$ (never)	$\Leftarrow$	$\Leftarrow$
4	$\epsilon_r \geq \Delta_l - eV_B$	$V_B \geq (\Delta_l - \Delta_r)/e$	$\Leftarrow$	$\Rightarrow$

Table 1: Tunnel processes 1–4. The table lists the conditions for quasiparticle energies ϵ which must be satisfied for the process to occur. In the central column we assume that the quasiparticles occupy the energy level of the band gap. Then, for positive bias voltages, process 1 is always possible, process 3 never, and the mutually exclusive processes 2 and 4 occur depending on the bias voltage being higher or lower than $(\Delta_l - \Delta_r)/e$. The right columns show the directions of quasiparticle and electron currents (cf. fig. 2).

sponds to a lowering of the Fermi level of the right electrode. The directions of quasiparticle and electron currents are compiled in table 1. Since excited quasiparticles relax to the gap edge within a very short time and since the operating temperature in our case is very low, the quasiparticles have an energy close to the energy gap. For the discussion in this section, we will assume that the quasiparticles exclusively occupy states with energies of the energy gap (i.e. $\epsilon_l = \Delta_l$ and $\epsilon_r = \Delta_r$). In reality, where the distribution of quasiparticles is different from a δ -like distribution (e.g. Fermi-Dirac distribution function for thermal excitation), the statements made here still hold in general, but become less stringent due to the presence of excited quasiparticles. In tunnel junctions with equal energy gaps, processes 2 and 3 are highly suppressed and only processes 1 and 4 were considered in previous works [5]. Processes 2 and 3 are only possible if the quasiparticles in the electrode from which they originate are excited above the energy gap or, if they occupy a higher energy level due to a larger energy gap, a situation found in hetero tunnel junctions.

Our present fabrication process creates tunnel junctions with electrodes of unequal energy gaps. This is caused by the proximity of tantalum and aluminium (see fig. 1). The electrode of the tunnel junction, which is in contact with the absorber, exhibits a higher energy gap than the other electrode of the tunnel junction. Quasiparticles which are created (e.g. by incident X-ray photons) in the tantalum absorber propagate therein by diffusion and get trapped into the tunnel junction layer with the enhanced energy gap. We assume this layer to be the left layer in fig. 2. For purpose of simplification we assume that the quasiparticles disappear from the tunnel junction once they have tunnelled. I.e. repeated tunnelling (involving process 4) does not occur since the quasiparticles leave the right layer of the tunnel junction, e.g. by rapid out diffusion into the wiring layer. Therefore, in case of $\Delta_l > \Delta_r$ and $V_B > 0$ it is sufficient to consider only processes 1 and 2. Again, the quasiparticles are assumed at the gap edge ($\epsilon_l = \Delta_l$).

Process 1 is possible for all positive bias voltages. It causes an electron current from left to right and with respect to the applied voltage a positive electrical current. The density of final states of the right layer into which the quasiparticles tunnel is a function of the applied bias volt-

age. The tunnel rate constant is maximum at zero voltage and reduces with increasing voltage.

Process 2 is only possible for voltages lower than $V_B < (\Delta_l - \Delta_r)/e$. It causes an electron current from right to left and thus a negative electrical current. The maximum negative current is obtained for a bias voltage equal to $(\Delta_l - \Delta_r)/e$. This negative current can easily surpass the positive current since the density of final states for this process can be much higher than for process 1. The combination of processes 1 and 2 yields a total negative electrical current in the bias voltage range $0 < V_B < (\Delta_l - \Delta_r)/e$ since the density of final states in the right electrode for process 2 is always higher than for process 1.

If the applied bias voltage is zero, the density of excess quasiparticles is reduced by both processes 1 and 2. Both processes transfer quasiparticles from left to right but the electrical current is opposite. Since the densities of final states for both processes are identical at $V_B = 0$, they exhibit equal probabilities and the net electrical current vanishes.

At bias voltages $V_B > (\Delta_l - \Delta_r)/e$ process 2 is forbidden and the negative component of the electrical tunnel current vanishes. The total current is again positive.

Process 3 is strongly suppressed and we neglect it in this discussion. It would require highly excited quasiparticles in the right layer.

Process 4 can only occur if the quasiparticles which have tunnelled via processes 1 or 2 are confined to the right layer. It provides a possibility for repeated tunnelling of quasiparticles. This situation prevails in other detectors discussed in the literature [6],[7]. However, for reasons of clarity, we will assume only thermally excited quasiparticles (operating temperature $T = 60$ mK) in the right layer but no excess quasiparticles. Thus, process 4 can be neglected for the discussion of the excess tunnel current.

3 Sample Fabrication

The goal of our new fabrication process was to create reproducible detectors with very clean superconducting layers [8]. In order to establish perfect quasiparticle trapping, a good interface between the absorber layer and the tunnel junction is required. It proved beneficial to deposit all

detector layers sample	layer thickness		
	a	b	c
Tantalum absorber	200 nm	400 nm	400 nm
Aluminium base electrode	700 nm	750 nm	350 nm
Oxide (tunnel barrier)	~ 2 nm	~ 2 nm	~ 2 nm
Aluminium counter electrode	700 nm	750 nm	700 nm
Tantalum adhesion layer	20 nm	20 nm	20 nm
Gold contact layer	100 nm	50 nm	50 nm
wiring method			
wiring material	Gold	Aluminium	Aluminium
wiring thickness	750 nm	800 nm	800 nm
insulation method	Polyimide	Al_xO_y	Al_xO_y
area of gold pad	$5450 \mu m^2$	$5680 \mu m^2$	$4700 \mu m^2$
fraction of gold pad covered by wiring	1.00	0.45	0.44

Table 2: Layer thicknesses of detectors a-c and information pertinent to the individual electrical contacts of the tunnel junctions. Before the wiring layer is attached (rows 1 and 2), the perimeter of the tunnel junction is electrically insulated by a layer of Polyimide or Al_xO_y . The area of the tunnel junctions is $14,000 \mu m^2$. Part of it is covered with the adhesion and the gold contact layer (row 4). A fraction (last row) of the gold is covered with the wiring layer.

detector layers in one vacuum cycle. In our previous fabrication process, which involved shadow masks, all materials were deposited within one vacuum chamber. This may have caused some cross contamination. The positioning of the shadow masks through which the different detector elements were deposited, required a sophisticated mechanical device inside the vacuum chamber. The positioning apparatus contained temperature sensitive elements, which prohibited baking at temperatures in excess of $\sim 120^\circ C$. Thus, due to outgassing, additional impurities may have been incorporated into the detector layers.

The new fabrication process separates the deposition of the detector layers and their patterning. A three chamber ultra high vacuum system is employed to deposit epitaxial tantalum layers in one of its chambers. The aluminium films of the tunnel junctions are deposited in the second chamber and the tunnel barrier fabrication, as well as the deposition of a gold contact layer, are performed in the third chamber which also serves as load lock. Since dedicated vacuum chambers exist for the different materials, cross contamination is avoided, and since the metal films are deposited on whole wafers (avoiding the positioning apparatus for in situ mechanical shadow masks), vacua better than 10^{-10} mbar can be achieved. After fabrication of whole wafer film sandwiches, the detectors are patterned using standard photolithographical methods and several etch processes (Ar ion, reactive, and wet etching). To complete the entire detector, insulating and wiring layers are attached. Table 2 lists the layer thicknesses and wiring methods of the devices discussed in this paper.

4 Charge Yield in Hetero Tunnel Junctions

A charge sensitive preamplifier connected to a tunnel junction integrates the electrical tunnel current and produces an output signal proportional to the charge signal Q_t . Q_t is the charge which has tunnelled across the tunnel barrier and it is a fraction of the charge Q_0 which is initially available for tunnelling. The efficiency of a tunnel junction for converting excess quasiparticles into a charge signal is given by the ratio of the tunnel rate for the electron current $\gamma_{T_{el}}$ and the total quasiparticle loss rate $\gamma_{V_{tot}}$ [9].

$$Q_t = Q_0 \cdot \frac{\gamma_{T_{el}}}{\gamma_{V_{tot}}} \quad (2)$$

We consider here a situation in which excess quasiparticles disappear after having tunnelled once. Thus, tunnelling also is considered a loss process. In case of a tunnel junction with electrodes of equal energy gaps ($\Delta_l = \Delta_r$), the rate constants for tunnelling of electrons $\gamma_{T_{el}}$ and for transfer of quasiparticles $\gamma_{T_{qp}}$ across the tunnel barrier are equal and we are able to write ($\gamma_{T_{el}} = \gamma_{T_{qp}} = \gamma_T$) [9]:

$$Q_t = Q_0 \cdot \frac{\gamma_T}{\gamma_T + \gamma_V} \quad (3)$$

Here, γ_V is the decay rate of quasiparticles within the trapping layer (left layer) of the tunnel junction. γ_T is predominantly governed by process 1 where the electron current and the transfer of quasiparticles occur in the same direction.

In case of a tunnel junction with unequal energy gaps ($\Delta_l > \Delta_r$) and excess quasiparticles in the layer with the higher energy gap, the rate constants $\gamma_{T_{el}}$ and $\gamma_{T_{qp}}$ are different. For voltages below $(\Delta_l - \Delta_r)/e$, processes 1 and 2 occur, whereby the rate for tunnelling of electrons $\gamma_{T_{el}}$ is given by the difference of the rates for these processes. The quasiparticle loss rate due to tunnelling $\gamma_{T_{qp}}$, however, is

the sum of the single rates for processes 1 and 2. Thus, for the amount of charge crossing the tunnel barrier we have to write:

$$Q_t = Q_0 \cdot \frac{\gamma_{T_{el}}}{\gamma_{T_{qp}} + \gamma_V} \quad (4)$$

The yield of charge signal is the ratio Q_t/Q_0 . For the calculation of the rate constants $\gamma_{T_{el}}$ and $\gamma_{T_{qp}}$ we make the following assumptions:

- excess quasiparticle density only in the left layer
- for excess quasiparticles a distribution according to eq. 5 is used
- excess quasiparticles disappear after having tunnelled
- thermal distribution of quasiparticles in the right layer of the tunnel junction
- branch mixing is much faster than tunnelling, i.e. $f^*(\epsilon, T, T^*) = 1 - f^*(-\epsilon, T, T^*)$
- tunnel process is energy conserving
- normalconducting density of states N_N is constant $N_N = N_N(0)$

In the limit $kT \ll \Delta_t$, the distribution function for quasiparticles in the left layer of our tunnel junctions is approximated by [10]:

$$f^*(\epsilon, T, T^*) = f(\epsilon, T) + c(x, t) \cdot \tilde{f}(\epsilon, T^*) \quad (5)$$

$f(\epsilon, T)$ is the Fermi-Dirac distribution function, $\tilde{f}(\epsilon, T^*)$ describes the distribution of excess quasiparticles, ϵ is the quasiparticle energy with respect to the Fermi energy E_F , and $g(\epsilon)$ is the ratio between the densities of states in the superconducting (N_S) and the normalconducting (N_N) state.

$$\begin{aligned} f(\epsilon, T) &= \frac{1}{1 + \exp(\frac{\epsilon}{kT})} & g(\epsilon) &= \frac{N_S}{N_N} = \frac{\epsilon}{\sqrt{\epsilon^2 - \Delta^2}} \\ \tilde{f}(\epsilon, T^*) &= \exp(-\frac{\epsilon}{kT^*}) & \text{for } \epsilon \geq 0 \\ \tilde{f}(\epsilon, T^*) &= 1 - \exp(\frac{\epsilon}{kT^*}) & \text{for } \epsilon < 0 \end{aligned} \quad (6)$$

Since we do not consider here a spatial variation of the quasiparticle density within the left layer of the tunnel junctions nor a time dependence, we assume $c(x, t) = 1$ for the following calculations.

The excess currents are calculated as the difference of currents between a tunnel junction with an excess density of quasiparticles given by eq. 5 in the left layer (temperature T^*) and the right layer at temperature T and a tunnel junction with both layers at the operating temperature T of the tunnel junction. T^* is the temperature which corresponds to an excess number of quasiparticles caused by the absorption of energy E_0 and is calculated according to:

$$N_{exc} = \frac{E_0}{1.68 \cdot \Delta_t} = 4 N_N \cdot Ad \cdot \int_0^\infty \tilde{f}(\epsilon, T^*) g_t(\epsilon) d\epsilon \quad (7)$$

N_{exc} is the number of excess quasiparticles and 1.68 corrects for the effective amount of energy required to create one

quasiparticle [11]. A and d are the area and thickness of the left electrode of the tunnel junction (trapping layer).

The total excess current for electrons (quasiparticles) based upon processes 1–4 is given by:

$$\Delta I_{exc} = \frac{1}{e R_{NN}} \int_0^\infty \tilde{f}(\epsilon, T^*) \cdot g_t(\epsilon) \cdot (g_r(\epsilon + eV_B) \mp g_r(\epsilon - eV_B)) d\epsilon. \quad (8)$$

The '-' sign applies to the rate of electron current and the '+' sign to the rate of quasiparticle transfer. R_{NN} is the resistance of the tunnel junction at voltages $V_B \gg (\Delta_t + \Delta_r)/e$ and accounts for the characteristic of the tunnel barrier. If we define $\Delta I_{exc} = e \cdot \gamma_{T_{el}/qp} \cdot N_{exc}$ we arrive at the tunnel rate constants:

$$\begin{aligned} \gamma_{T_{el}/qp} &= \frac{1}{4e^2 N_N R_{NN} Ad} \cdot \\ &= \frac{\int_0^\infty \tilde{f}(\epsilon, T^*) g_t(\epsilon) \cdot (g_r(\epsilon + eV_B) \mp g_r(\epsilon - eV_B)) d\epsilon}{\int_0^\infty \tilde{f}(\epsilon, T^*) g_t(\epsilon) d\epsilon} \end{aligned} \quad (9)$$

The amount of signal produced by a charge sensitive preamplifier connected to a tunnel junction is given by eq. 4. γ_V therein covers all quasiparticle losses besides tunnelling. We assume γ_V to be independent of the bias voltage V_B for the discussion in this paper. However, this is not the general case. A situation, where γ_V also depends on V_B is discussed e.g. in ref. [12]. Fig. 3 shows the bias voltage dependence of the rate constants $\gamma_{T_{el}}$ and $\gamma_{T_{qp}}$ in the upper part of the figure. The lower part of the figure shows the ratio $\frac{\gamma_{T_{el}}}{\gamma_{T_{qp}} + \gamma_V}$ for different values of γ_V . Since $\gamma_{T_{el}}$ and $\gamma_{T_{qp}}$ are strongly dependent on V_B it is advised to operate the detector at a fixed, well stabilized bias voltage. A slow drift of the bias voltage causes the responsivity $\frac{\partial Q_t}{\partial E}$ of the detector to vary, thereby deteriorating the energy resolution.

Fig. 4 suggests to operate detectors a and b at voltages $V_B > 80 \mu V$, where $\frac{\gamma_{T_{el}}}{\gamma_{T_{qp}} + \gamma_V}$ becomes less dependent on bias voltage. However, due to non-ideal behaviour of our tunnel junctions, their bias current increases strongly with bias voltage. Since high bias currents and low dynamical resistances $R_D = \frac{\partial V}{\partial I}$ cause increased electronic noise, it is not favourable to operate our detectors in this regime of high bias voltages [13]. An optimum for the bias voltage has to be found in order to have high signal and low electronic noise. The demand for high signal and bias voltage independence requires high bias voltages, while minimum electronic noise is usually obtained at low bias voltages. It is therefore not sufficient to provide tunnel junctions with a high quality factor $Q = R_D/R_{NN}$ only for low bias voltages. The quality factor has to remain high also for bias voltages well above $(\Delta_t - \Delta_r)/e$.

Figure 3: Rate constants for quasiparticle current γ_{Tqp} and for electron current γ_{Tel} according to eq. 9 as a function of bias voltage V_B normalized to γ_0 . The energy gaps used for this calculations were $\Delta_l = 0.22 \text{ meV}$ and $\Delta_r = 0.18 \text{ meV}$. The temperatures were $T^* = 175 \text{ mK}$ and $T = 60 \text{ mK}$. The set of graphs in the lower part of the figure shows the charge yield $\frac{\gamma_{Tel}}{\gamma_{Tqp} + \gamma_V}$ (eq. 4) for various values of γ_V .

5 Experimental Results

The detectors were operated at a temperature of 60 mK . An ^{55}Fe X-ray source was used for irradiation experiments. This radioactive source emits X-ray photons of 5.89 keV (K_α) and 6.49 keV (K_β) energy with an abundance ratio of $\approx 7 : 1$. Irradiation of the entire detector was performed. For the measurement pertaining to the bias voltage dependence of the tunnel current only charge signals resulting from absorption of K_α photons in the proximity layer underneath one tunnel junction were used. Energy spectra were recorded for various bias voltages and the position of the K_α peak was taken from these energy spectra. The position of the K_α peak is a direct measure of the charge yield according to eq. 4. The transfer function of the entire electronic read-out chain was monitored by injecting a known amount of charge into the test input of the charge sensitive preamplifier. The dynamical resistance of the tunnel junction which changes with bias voltage enters in this transfer function and thus causes a small change of electrical response. The data for samples b and c are corrected for the varying electrical response. No calibration data are available for sample a. In this case, the vertical error bars are extended to the maximum deviation of electrical response

Figure 4: Experimental data and curves of charge yield for three different samples. The pertinent data on layer thicknesses and wiring layer parameters are listed in table 2. The parameters used to calculate the solid curves are given in the text. The experimental data are normalized such that the maximum negative signal gives a charge yield of “-1”.

found for samples b and c.

Fig. 4 shows the charge yield as a function of bias voltage. This yield $\frac{\gamma_{Tel}}{\gamma_{Tqp} + \gamma_V}$ is given in arbitrary units, as the amount of originally created charge bears a huge uncertainty. Measurements have been performed for positive bias voltages only, except for sample c. To verify the accuracy of our bias voltage measurement and to exclude any offset in bias voltage, we show in the inset of fig. 4c also the data for negative bias voltages.

Samples a and b exhibit maximum negative signals at a bias voltage of $\sim 38 \mu V$. Both samples have aluminium lay-

ers of $\sim 700\text{ nm}$ thickness. Although the thicknesses of the tantalum layers differ by a factor of two and the method of attaching an electrical contact to the tunnel junctions is very different between samples a and b, the difference of energy gaps appears to be approximately the same. The situation is different for sample c. Here, the aluminium layer of the tunnel junction which is in contact with the absorber is only 350 nm thick while all other parameters are almost the same as for sample b. It is obvious from fig. 4 that the energy gap of the proximity layer of sample c is enhanced compared with samples a and b. If we assume that the energy gap of the right electrode is that of plain aluminium ($\Delta_r = 0.18\text{ meV}$), then the energy gaps of the proximity layers are: $\Delta_l \approx 0.215\text{ meV}$ for a, $\Delta_l \approx 0.220\text{ meV}$ for b, and $\Delta_l \approx 0.275\text{ meV}$ for c. The energy gaps of the left electrodes are deduced from the maximum negative signals which occur at a bias voltage of $V_B = (\Delta_l - \Delta_r)/e$. The solid curves in fig. 4 show the charge yield according to eq. 4 for these energy gaps. The quasiparticle losses γ_V in units of γ_0 are: 0.3, 0.3, and 1.2 for samples a-c. The "temperatures" T^* for the excess densities of quasiparticles according to eq. 7 were 172 mK , 175 mK and 225 mK , respectively. A distribution of quasiparticles according to eq. 5 was used. The deviation of the solid curve from the experimental data, especially for bias voltages above $(\Delta_l - \Delta_r)/e$, is a hint towards a non-constant energy gap Δ_l and/or a distribution of quasiparticles different from f^* (see eq. 5). This behaviour is not surprising. The model we have applied here is just a tunnel junction with unequal energy gaps and a model distribution of quasiparticles according to eq. 5. Nevertheless, this simple approximation gives already the qualitative behaviour. The input of theory pertaining to the proximity effect and the quasiparticle distribution is required to explain the experimental data in fig. 4 more appropriately. We are aware that such models exist, but we find that there are too many free parameters for application to our samples and that our data can be explained by very different sets of parameters [14],[15].

6 Conclusions

We have experimentally demonstrated a tunnel process which causes an excess tunnel current flowing opposite to the tunnel current observed in a tunnel junction in thermal equilibrium. Such behaviour of hetero tunnel junctions may have reduced the charge signal in many detectors of similar structure and design.

The occurrence of negative signals could be avoided if the excess excitation were created in the junction layer with the lower energy gap. Thus, we propose to fabricate the layer into which the excess quasiparticles tunnel (right layer) of a material with a higher energy gap, preferably the material of the absorber again. This way, process 2 would be strongly suppressed and the tunnel current would be caused only by process 1.

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