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High resolution X-ray spectroscopy with superconducting tunnel junctions

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ABSTRACT

High resolution X-ray spectroscopy provides a powerful tool for the diagnosis of plasmas and extra terrestrial X-ray sources. We are developing detectors based on superconducting tunnel junctions which will provide position sensitive detectors with much better energy resolution than current state of the art CCD cameras. The amount of energy required to create a charge carrier in a superconductor is about three orders of magnitude smaller than in standard semiconductor detectors. Consequently, the energy resolution, especially in the energy range below a few keV, is significantly enhanced. The drawback of the necessarily small size of superconducting tunnel junctions has been compensated by a separation of X-ray absorber and detecting tunnel junction ('quasiparticle trapping'). We report on results with our detector which can resolve the 5.89 keV manganese line with an energy resolution of better than 60 eV. In addition position resolution better than 5 μm has been demonstrated with an absorber 470 μm long. To match the detector to the spot size of the X-ray optics in use, a multi element detector is under development.

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1. INTRODUCTION

Progress in many fields of physics has often been initiated by the availability of new detection techniques. In the domain of astrophysics, detectors which offer resolving powers close to that of crystal spectrometers or gratings, but with a counting capability of surface barrier semiconductor detectors would be highly beneficial.[1,2]

Detectors engaging effects present only at very low temperatures, like superconductivity, might fill the gap between the detectors mentioned above. Superconducting tunnel junctions could be very useful for the spectroscopy of X-rays in the energy range from 100 eV up to several keV. X-rays in this energy range provide a very strong tool for the diagnosis of extra terrestrial plasmas and other X-ray emitters. From the intensities and ratios of X-ray lines it should be possible to determine gas temperature, density, element abundance, or ionisation states of X-ray sources.[3] Such a detector should be able to resolve line features across an X-ray continuum with sufficient resolution. In addition to very high energy resolution, position resolution might render plasma diagnosis even more meaningful.

2. SUPERCONDUCTING TUNNEL JUNCTIONS

The electronic energy gap in semiconductors commonly used for particle and radiation detection is of the order of a few eV. Progress in the last decades has led to a situation where the energy resolution for semiconducting detectors is indeed limited by the statistics of charge carriers (Fano factor limited) released in an absorption event.[4]

Further improvement in energy resolution seems possible by employing detector materials with significantly reduced energy gap. The number of charge carriers generated by energy absorption is then increased by the ratio of effective energy gaps, the energy resolution approximately by the square root thereof. The energy gap of superconductors is of the order of meV, being smaller by three to four orders of magnitude compared to semiconductors. The statistics of charge carriers should then improve by one or two orders of magnitude.

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With advanced techniques of semiconductor fabrication it became possible to integrate the input stage of the read out amplifier on the detector chip itself. Thus, the electrical capacitance present at the input FET is very low and the electronic noise gets negligibly small. Such advanced techniques are not yet available for superconducting detectors because of the incompatibility of superconductors and semiconductors. Also, by implication, the electrical capacitance of a superconducting tunnel junction by itself is considerably high limiting the achievable signal to noise ratios. With progress in technical fields one should eventually be able to actually utilize the high statistics of charge carriers in superconducting detectors.

A superconducting tunnel junction consists of two superconducting metal films which are separated by a thin tunnel barrier (thickness: typically 10 Å to 20 Å). The tunnel current flowing across the tunnel barrier is proportional to the density of quasiparticles, i.e. electrons released from breaking a Cooper pair. Energy deposited in a tunnel junction is to a great part used to create quasiparticles which can then be measured via a change in tunnel current.[5]

Superconductors exhibit an energy gap in the excitation spectrum for single electrons when cooled to temperatures below a critical temperature T_C. Electrons in a small energy range above and below the Fermi energy E_F condense into Cooper pairs, a process well described by the BCS-theory. The ground state of Cooper pairs is lower in energy by Δ with respect to the lowest allowed state of quasiparticles. By deposition of an energy $\geq 2\Delta$ a Cooper pair can be destroyed, resulting in the creation of two quasiparticles. These excited quasiparticles then contribute to the tunnel current in a suitably biased tunnel junction.

According to the BCS-theory, the density of states n_S for electrons is given by:

$$n_S(E) = n_N(E) \cdot \frac{|E - E_F|}{\sqrt{(E - E_F)^2 - \Delta^2}} \tag{1}$$

with n_N the density of states in the normal conducting case and E the energy of quasiparticles. Because of the smallness of the energy gap, $n_N(E)$ can be considered constant, using the approximation of $n_N(E) = n_0$, the density of states at the Fermi energy. At finite temperature there exists a density of excited quasiparticles n(T):

$$n(T) = 2 \cdot n_0 \cdot \sqrt{2\pi\Delta kT} \cdot \exp\left(-\frac{\Delta}{kT}\right) \tag{2}$$

Superconducting tunnel junctions should be operated at low temperature ($T < 0.15\,T_C$) as the density of thermally excited quasiparticles is then small compared to densities of excess quasiparticles generated in typical absorption events.

In our experiments, the dc Josephson current flowing with no voltage drop across the tunnel barrier is suppressed by the application of a weak magnetic field parallel to the plane of the tunnel barrier.[6] At voltages V, in the range $0 < V < 2\Delta/e$, a thermal current flows. Due to the low operating temperatures in our experiments this current is well suppressed, leaving a tunnel current caused by the non ideal behavior of our superconducting tunnel junctions. If the voltage is increased to values above $2\Delta/e$, a steep rise in current is observed because two singularities in the densities of state, one with many occupied states and one with many empty states oppose each other. Increasing the voltage further leads to an ohmic current voltage characteristics as the influence of the singularities fades. For operation as a detector, a bias voltage V_B is chosen in the range $kT/e \ll V_B < 2\Delta/e$ and at a point where the differential resistance $R_D = \partial V/\partial I$ is maximal. The actual bias point on the current voltage characteristics is usually determined by properties of the tunnel junctions causing a deviation from the ideal behavior appearing in the current voltage characteristics.[7]

The tunnel process can be described with a tunnel rate γ_T, which can be calculated according to Fermi's Golden Rule. As the two metal films of a tunnel junction have differing thicknesses d_l,d_r the tunnel rate constants are

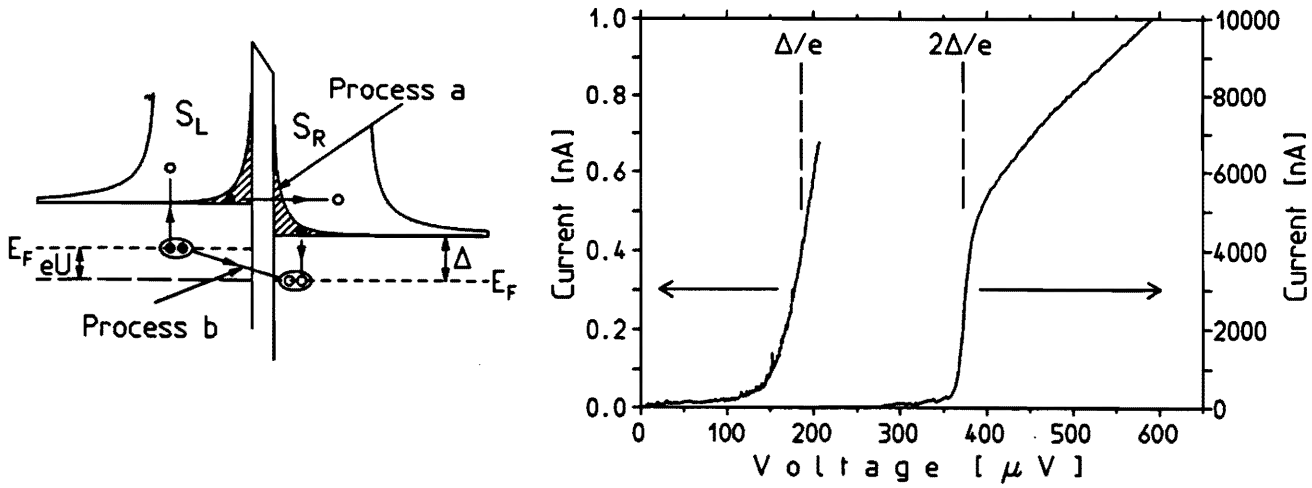

Fig. 1: On the left, the two dominant tunneling processes in a superconducting tunnel junction are shown. By process a, a quasiparticle tunnels from left to right. Process b transfers a quasiparticle from right to left via the exchange of a virtual phonon. In both cases, one electrical charge flows from left to right. On the right, a current voltage characteristics of one of our superconducting Aluminium tunnel junction is shown. The operating temperature is 60 mK. Two branches of the same device are shown with different current scales. The increase in current below the energy gap of the low current (left) branch may be due to non ideal properties of the superconducting metal films.

unequal for both films. It follows that:

$$\gamma_{T_{l,r}} = \frac{1}{2e^2 n_0} \cdot \frac{1}{R_{NN} A d_{l,r}} \cdot \frac{\Delta + eV}{\sqrt{(\Delta + eV)^2 - \Delta^2}} = \frac{1}{2e^2 n_0} \cdot \frac{1}{R_{NN} A d_{l,r}} \cdot F \tag{3}$$

R_{NN} is the 'normal conducting' resistance of the tunnel junction measured at voltages V well above $2\Delta/e$, and A is the area of the tunnel junction, where tunneling of quasiparticles is possible. With the conditions typical for our experiments, F is usually of order 1.5. The excess tunnel current I is given by:

$$I = \frac{e}{2} \cdot (\gamma_{T_{lr}} N_l + \gamma_{T_{rl}} N_r) \tag{4}$$

N_l and N_r are the numbers of quasiparticles excited in the left and right layers in the area A of the tunnel junction. If an equal amount of energy is absorbed in either film of the tunnel junction, an equal number of quasiparticles results. Due to the inequality of the tunnel rate constants, the height of the current signal observed is dependent on the film in which the absorption took place. For this reason, it follows clearly that direct absorption of energy in a tunnel junction is not good for a practical detector, but it is necessary for the understanding and diagnosis of superconducting tunnel junctions.[8]

There exist two tunnel processes (cf. fig. 1):

Process a: A quasiparticle generated in the left layer tunnels into the right layer. There, it relaxes down to the energy gap edge under emission of a phonon with energy $e \cdot V$. After completion of process a, one quasiparticle and one electrical charge have been transferred from left to right.

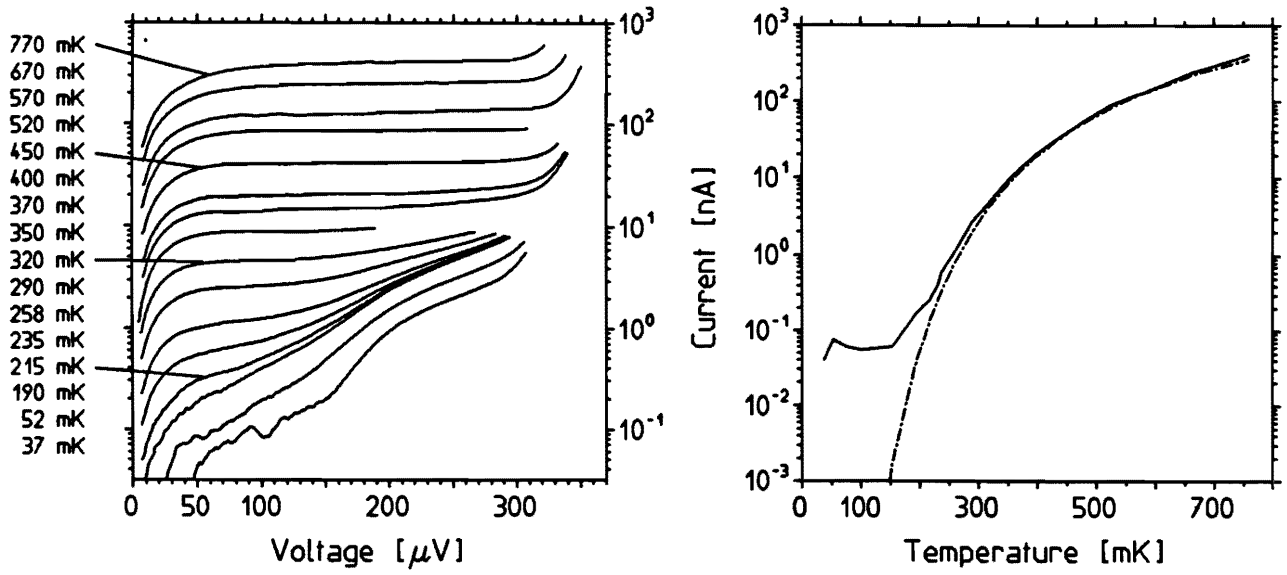

Fig. 2: In the left part of the picture, several branches of current voltage traces are shown for various operating temperatures. The vertical axis is logarithmic. In the right diagram, the current level at fixed voltage from the experiment (solid line) together with the calculation according to BCS-theory (dot dashed line) is plotted versus temperature. The deviation at low temperatures may be attributed to the presence of non idealities in the tunnel junction.

Process b: A quasiparticle generated in the right layer and one electron from a Cooper pair in the left layer recombine to form a Cooper pair on the right side. An energy Δ is liberated in the relaxation of the quasiparticle on the right side, while an energy $e \cdot V$ results from the electron crossing the tunnel barrier. The total energy $\Delta + e \cdot V$ is spent to excite the remaining electron of the destroyed Cooper pair in the left layer to an energy of $e \cdot V$ above the gap edge, from where it relaxes back to the energy gap under emission of a phonon with energy $e \cdot V$. Process b takes an electrical charge from left to right (like process a) but takes a quasiparticle from right to left.

Both processes lead to a unidirectional flow of electrical current. Consequently, the polarity of the signal is independent of whether the excess quasiparticle density is generated in the left or in the right layer.[9]

The timely and spatially varying densities of quasiparticles and of 2Δ phonons can be described with a set of coupled differential equations.[10] At the low temperatures prevailing in our experiments, and assuming that the processes occurring during the first few ns after energy absorption are not of interest, the equations for 2Δ phonons can be omitted, leaving only the equations for quasiparticles for the two metal layers. Furthermore, if 'back tunneling' of quasiparticles can be disregarded, the equations for quasiparticles in the left and in the right layers decouple and only one equation remains:

$$\dot{n} = -R \cdot n^2 - \left(\frac{\gamma_T}{2} + \gamma_V\right) \cdot n + \Delta n \tag{5}$$

R is a constant characterizing the recombination of two quasiparticles, γ_V and γ_T are the rate constants for a loss process of single quasiparticles and for the tunneling process. As we operate at very low temperatures, the term $R \cdot n^2$ can be omitted. Likewise diffusion of quasiparticles can be disregarded as long as tunnel volume and junction volume coincide, or in case the excitation occurs at a constant position within the tunnel junction. The latter situation applies to our experiments. The equation for quasiparticles then becomes:

$$\dot{n} = -\left(\frac{\gamma_T}{2} + \gamma_V\right) n = -\gamma n \tag{6}$$

with $\gamma = \gamma_T/2 + \gamma_V$ representing a rate constant with which the quasiparticle density returns to an equilibrium state. Single quasiparticles can disappear, i.e. stay localized at positions of reduced energy gap, by a variety of reasons, such as presence of impurities, trapped magnetic flux, dislocations, or normal conducting cores.

The presence of normal conducting regions also shows up in the temperature dependence of the thermal current of a tunnel junction. In contrast to an ideal superconducting tunnel junction (S-I-S), a real tunnel junction exhibits an admixture of partly normalconducting-superconducting tunnel junction (S-I-N) and to an even lesser fraction normalconducting-normalconducting tunnel junction (N-I-N) (see figs. 1 and 2).

With the operating temperature decreasing, the tunnel current follows very well the expected behavior of an S-I-S tunnel junction. At lower temperatures, the tunnel current does not reduce further with temperature as the temperature independent current of a N-I-N tunnel junction remains. The fraction of normalconducting regions in a superconducting film can also be determined from the current voltage characteristics of a tunnel junction at lowest temperature. See fig. 1, were an onset of additional current at a voltage near Δ/e can be observed. This is an indication for the presence of normalconducting parts of the tunnel junction films.

3. SUPERCONDUCTING ABSORBERS AND QUASIPARTICLE TRAPPING

Considerations like large absorber sizes, a desire to optimize absorber and tunnel junctions separately, or the need of a unique signal response require the separation of absorber and tunnel junctions.

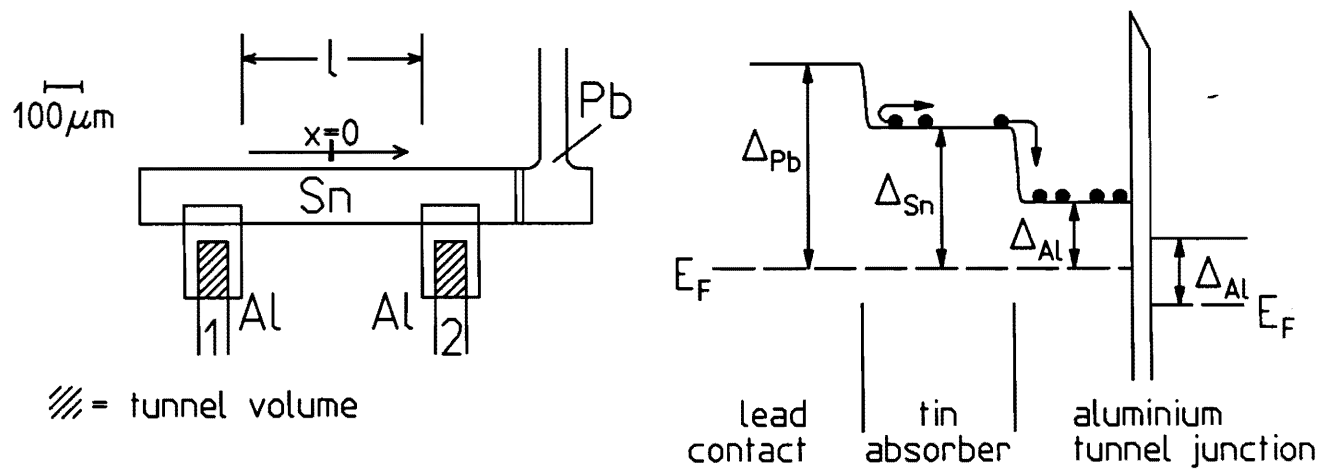

Fig. 3: On the left side, the arrangement of the detector is shown: The tunnel junctions consist of two Aluminium films separated by a thin tunnel barrier. The right side shows the energy level diagram for quasiparticles: Quasiparticles created in the Tin absorber are trapped by one of the Aluminium tunnel junctions where they have to tunnel before having a chance to escape into the contact pad of the particular tunnel junction.

If a quasiparticle is excited by an energy E above its lowest possible energy state, the band gap, it relaxes down in energy with a rate proportional to E^3.[11] If superconductors with differing energy gaps are connected metallically, potential wells for quasiparticles are generated, and consequently quasiparticles are concentrated at the positions of smallest energy gap.[1,12]

We use an absorber made of Tin with an intermediate energy gap. Two Aluminium tunnel junctions with small energy gaps are attached to the absorber. An electrical contact defining the common potential of one film of the tunnel junctions is facilitated by a Lead lead with high energy gap connected to the absorber.

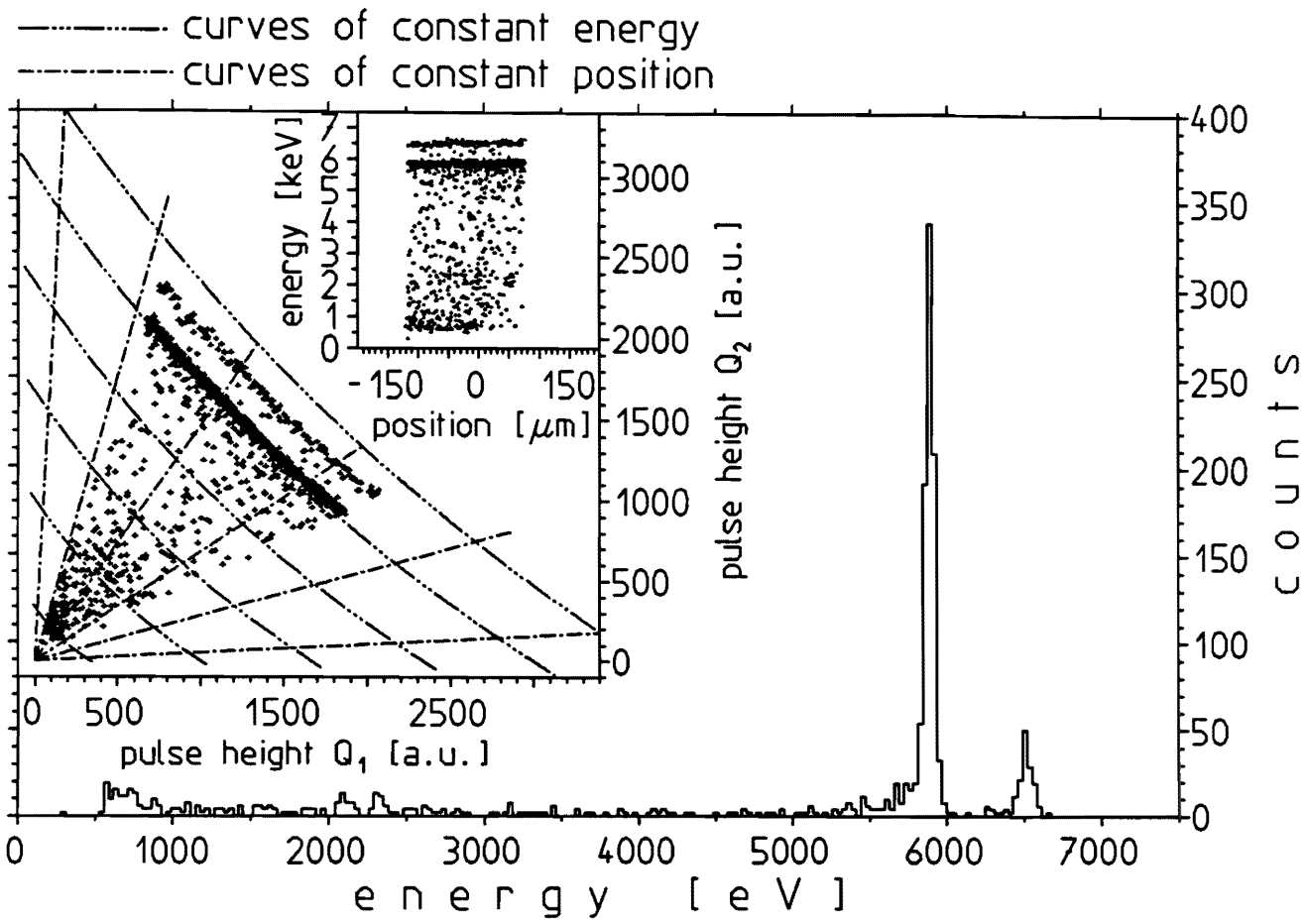

Fig. 4: The energy spectrum resulting from the irradiation of part of the absorber with X-ray photons emitted by an ^{55}Fe-source. The energy resolution derived from the well known difference is better than 60 eV (FWHM) for the K_α line. In the inset, the original data are shown in the Q_1 vs. Q_2 plane superimposed with lines of constant energy and constant position and the transformation into the energy vs. position plane.

Quasiparticles created in the absorber of length ℓ by the absorption of an X-ray photon propagate therein by diffusion (diffusion constant D) and get trapped by one film of the superconducting tunnel junctions. They cannot leave the absorber otherwise as the attached Lead contact pad blocks the way out. For reasons already discussed, a decay of the quasiparticle density has to be superimposed, with a rate constant γ_D. The equation valid for the motion of quasiparticles in the absorber is:

$$(\partial_t - D \cdot \partial_x^2 + \gamma_D)\, n(x,t) = 0 \tag{7}$$

The boundary condition is $n(\pm\ell/2, t) = 0$ and the initial quasiparticle density after the absorption of an X-ray photon at position x_0 is given by $n(x,0) = E_0/\omega \cdot \delta(x - x_0)$. After solving equation 7, a relation between measured signal heights Q_1, Q_2 and E_0, x_0, energy and position can be given:

$$E_0 = \frac{\omega}{e \cdot K} \cdot \sqrt{Q_1^2 + Q_2^2 + 2Q_1Q_2\cosh\alpha} \quad \text{and} \quad x_0 = \frac{\ell}{2\alpha} \cdot \ln\left(\frac{Q_1 e^{-\frac{\alpha}{2}} + Q_2 e^{\frac{\alpha}{2}}}{Q_1 e^{\frac{\alpha}{2}} + Q_2 e^{-\frac{\alpha}{2}}}\right) \tag{8}$$

with K the yield of quasiparticles actually registered ($0 \leq K \leq 1$), ω the effective energy necessary to create one single charge carrier, and $\alpha = \sqrt{\ell^2 \gamma_D / D}$.

The energy resolution for 5.89 keV X-rays is better than 60 eV. Experiments up to present have all been carried out with standard charge sensitive preamplifiers (CANBERRA 2003 BT) designed for the use with semiconductor detectors, and operating at room temperature. Although the design considerations for amplifiers well matched to detectors with superconducting tunnel junctions are different from those applied in the CANBERRA 2003 BT it represents a reasonable first choice. Criteria for designing a properly matched preamplifier are discussed in the next section. The energy resolution demonstrated so far is limited by electronic noise of the preamplifiers with the large electrical capacitance of the superconducting tunnel junctions.

As suggested by the model (eqs. 7 and 8), position resolution of the detector should be of the same order of magnitude as the energy resolution. With an absorber length of 470 μm the expected position resolution is some few μm. It is experimentally difficult to define positions for a selective irradiation with such an accuracy. Therefore, an absorber was fabricated with five sections of differing thicknesses. For the 6 keV X-rays, and the thin films used, the absorption efficiency is still nearly proportional to the absorber thickness. The two sections with enhanced thickness with respect to the other three sections should show up in the spectrum of positions with an increased number of registered events. A comparison between an optical measurement and the result from the irradiation gave a very good agreement. Besides the experimental value, the position resolution can also be calculated from the measured energy resolution. Both methods led to a position resolution of better than 5 μm.

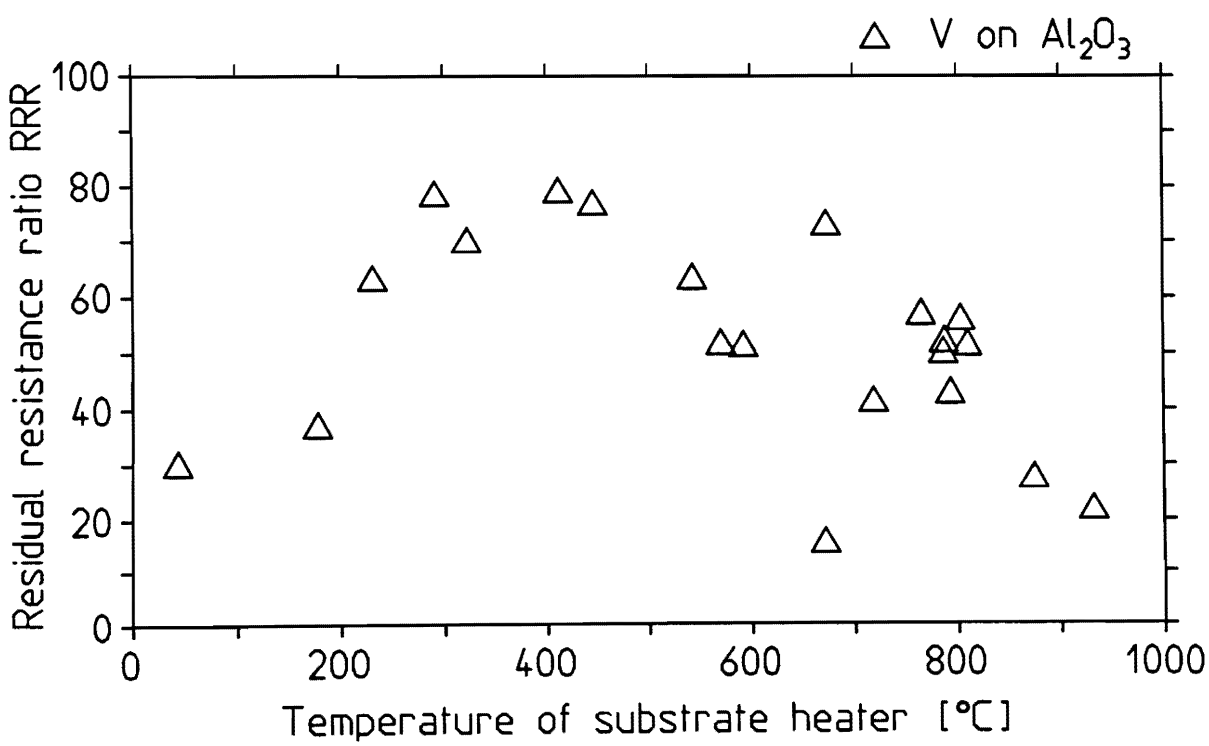

Fig. 5: Residual resistance ratios RRR for thin films epitaxially grown on Al_2O_3 substrates. Except for the substrate temperature, all other growth parameters were kept unchanged. 412°C was the optimal substrate temperature.

The size of the absorbers is limited: The width of the absorbers is confined because the entire width should be covered with a superconducting tunnel junction. A large width implies a large electrical capacitance of the tunnel junction and thus imposes a limitation for actual designs (electronic noise increases with capacitance). The length of the absorber is limited because there is a competition of quasiparticle diffusion from the spot of creation to the trapping zone, i.e. the superconducting tunnel junction and the decay of the quasiparticle density.

Tin has been used as absorber in initial detector tests, but exhibits some disadvantages which we hope to remedy by the use of Vanadium as absorber material. 'Quality' of an absorber in terms of quasiparticle diffusion is expressed in the mean free path for electrons and the lifetime of an excess density of quasiparticles against processes removing quasiparticles from the density for which eq. 7 is valid.

The mean free path of quasiparticles is limited by impurities, dislocations, and surfaces. The latter poses no problem because the absorber films have to be thick anyhow compared to the practically obtainable mean free path in order to get sufficiently high X-ray absorption efficiency. Impurity concentration is minimized by the use of zone refined single crystals as evaporation material and running the fabrication process in an ultra high vacuum deposition system. By proper choice of substrate temperature and evaporation rate, dislocations in the absorber films can be greatly reduced.

The residual resistance ratio RRR $= \bar{\ell}/\bar{\ell}_{300}$ is proportional to the mean free path, if impurity scattering can be neglected at room temperature. Although the connection between RRR and $\bar{\ell}$ can be calculated easily the entering values for n, the density of electrons partaking in the electrical transport and m*, their effective mass cannot be determined readily. Thus, a value for $\bar{\ell}_{300}$ has been determined experimentally by observing the influence of surface scattering on the mean free path. Several theoretical models have been applied and a mean value of $\bar{\ell}_{300} = 40\,\text{Å} \pm 28\,\text{Å}$. With a maximum value of 79 for RRR, the mean free path amounts to 3160 Å. With an assumed lifetime for quasiparticles of $\approx 5\,\mu s$ an absorber length of 2 mm should be possible.

4. ELECTRONIC READ OUT SYSTEM

Superconducting tunnel junctions require read out electronics differing from that used for standard semiconductor detectors. The most influential quantities for the design of preamplifier and shaping amplifier are listed in the following table:

Detector type:	**Semiconductor**	**Superconductor**
elec. capacitance	50 pF	1000 pF
dyn. resistance	$\approx$ GΩ	5 kΩ – 1 MΩ
current pulse shape	delta pulse	expon. decay
length of pulse	$\approx$ ns	10 μs – 500 μs

To efficiently collect the charge released in a detector with a charge sensitive preamplifier, long integration times $\tau_E = R_F \cdot C_F$ of the order of $\approx$ ms have to be realized by proper choice of the feedback components of the preamplifier. R_F is the resistor and C_F the capacitor in the feedback loop of the preamplifier. τ_E required to be long suggests C_F and R_F being large. On the contrary, R_F cannot be chosen too large because R_D, the dynamical resistance of the tunnel junction multiplied by the open loop gain of the amplifier block G appears in parallel to the feed back resistor, giving a maximum value for R_F. C_F should not be too large because the output of the charge sensitive preamplifier is inversely proportional to C_F. Besides a specialized preamplifier capable of dealing with the modified detector parameters listed in the table above, a matched shaping amplifier with shaping times at least one order of magnitude longer than in conventional spectroscopy amplifiers is required. Signal measurement is performed with charge sensitive preamplifiers. Current sensitive preamplifiers were used only to study the time behavior of the pulses which gave insight into the diffusion processes of quasiparticles.

The large electrical capacitance of superconducting tunnel junctions has consequences for the selection of the input FET of the preamplifier. FETs developed for semiconductor detectors exhibit low input capacitance, because the series noise contribution is proportional to the parallel capacitance at the input of the charge sensitive preamplifier. The total parallel capacitance is: $C_{tot} = C_D + C_F + C_i$, with $C_D \approx 50\,pF$ the detector capacitance, $C_F \approx 2\,pF$ the feedback capacitance, and $C_i \approx 10\,pF$ the gate capacitance of the FET. All values are taken for semiconductor detectors, where C_D is the unavoidable capacitance. Design of the preamplifier is such that least additional capacitances are present. The open loop gain of the amplifying block is proportional to the transconductance g_m of the input FET. With the relationship $\omega_T = g_m/C_i$, with ω_T the transit frequency a constant for silicon J-FETs, a high open loop gain and a low input capacitance are mutually exclusive and an optimum has to be found. Using a simple model of a parallel plate capacitor the capacitance of a superconducting tunnel junction is typically some 100 pF up to nF in our experiments. This permits a higher input capacitance of the input FET. The result is a larger g_m which increases the open loop gain of the amplifying block. With the large detector capacitance and limited upper values for the dynamical resistance of superconducting tunnel junctions, a high open loop gain is indeed important.

A charge sensitive preamplifier with an NJ3600 FET made by Interfet has been designed. It consists of the NJ3600 as input FET, in cascode with a common base transistor for impedance conversion loaded with a constant current source.[13] The signal from the charge sensitive loop is further amplified by a factor of 12 before being presented at the output connector. An open loop gain of 15,000 is established. A feedback capacitor of 10 pF and a feedback resistor of 100 MΩ are used, resulting in a charge sensitivity of 100 mV/pC and an integration time of 1 ms. The equivalent noise charge (ENC) at 20 μs semi gaussian shaping is lower than 700 e^- rms ($C_D = 0\,pF$).

The shaping amplifier consists of a differentiation stage with adjustable pole zero cancellation, followed by an active filter network of five integrators. Equal shaping time constants for differentiation and integration of $\tau = 20\,\mu s$ have been established. A signal gain adjustable from 1 to 75 is implemented. The total output noise over the whole frequency range is lower than 2 mV pp, being smaller than the digitizing noise of the succeeding ADCs.

5. CONCLUSIONS

With a detector consisting of a Tin absorber (470 μm long) and two Aluminium tunnel junctions attached to it, we have demonstrated an energy resolution better than 60 eV (FWHM) at 6 keV. In addition, position resolution is better than 5 μm. We also gave a clear demonstration that quasiparticle trapping works.

Further progress can be made by replacing the Tin absorbers with Vanadium absorbers, which already exhibit a electron mean free path length exceeding that of our Tin films. For progress in energy resolution, we have designed and fabricated electronic equipment well matched to the characteristics of our detectors.

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