High-resolution x-ray spectra measured using tantalum superconducting tunnel junctions

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The spectral response of a 100×100 μm^2 tantalum based superconducting tunnel junction to 5.9 keV x-ray photons from a ^{55}Fe source has been studied. In full illumination the energy resolution for the Mn K_α line complex is 56 eV, dominated by spatial nonuniformity in the response of the detector. When illuminating selectively a 5–10 μm diam spot in the center of the detector, the energy resolution improves to 22 eV, corresponding to 15.7 eV for the individual Mn $K_{\alpha 1}$ and Mn $K_{\alpha 2}$ lines. This exceeds the predicted theoretical energy resolution of 7.3 eV for this type of device by only a factor of ∼2. © *1998 American Institute of Physics.* [S0003-6951(98)00125-9]

Superconducting tunnel junctions (STJs) are investigated extensively as photon and particle detectors because of their predicted high energy resolving power.[1] This high energy resolution arises from the much lower energy necessary to generate detectable electronic excitations, compared to semiconductor- or gas-based detectors. In the case of a superconductor these excitations (quasiparticles) are produced by the breaking of Cooper pairs, which typically requires ∼meV. For a common superconductor as Nb, the number of quasiparticles produced by the absorption of a photon with energy E is:

$$N_0(E)=\frac{E}{\epsilon}\pm\sqrt{\frac{E}{\epsilon}F}. \tag{1}$$

Here $\epsilon\approx1.74\Delta$ (with 2Δ the energy gap of the superconductor) is the average energy required to generate one quasiparticle and $F=0.22$ is the Fano factor.[2,3] The quasiparticles can be detected through tunneling across the thin insulating barrier of a STJ. The amplitude of the signal pulse measured after the absorption of a photon will, in a first approximation, be proportional to the number of generated quasiparticles and, thus, to the energy of the photon. The fundamental limit for the energy resolution is set by the Fano factor and would be $\Delta E_{\mathrm{Fano}}\approx3$ eV [full width at half maximum (FWHM)] for a 6 keV x-ray photon in a tantalum STJ, assuming the values for F and ϵ are similar to those calculated for Nb. In a practical STJ detector additional statistical fluctuations occur in the number of tunneled electrons. For a symmetrical STJ as used for this work, the limiting energy resolution arising from statistical fluctuations is given by:[4,5]

$$\Delta E_{\mathrm{stat}}=2.355\sqrt{\epsilon E\left(F+1+\frac{1}{\langle n\rangle}\right)}, \tag{2}$$

with $\langle n\rangle$ the average number of tunnel processes per quasiparticle. Typically, the statistically limited energy resolution of a Ta based STJ with $\langle n\rangle\geqslant10$ will be $\Delta E_{\mathrm{stat}}\approx7$ eV for 6 keV x rays. Further degradation of the energy resolution can be envisaged due to electronic noise and to spatial nonuniformities in the response of the detector.[6,7] Equation (2) has been shown to be fully valid for Ta-based devices illuminated with lower energy optical photons.[8] At these energies the additional contribution due to spatial nonuniformities is negligible. The best results for energy resolution at $E=5.9$ keV for a STJ are 29 eV for a Nb-based device with 200 nm thick Al trapping layers,[9] and 27 eV for an Al device.[10] While these results are impressive they are still inadequate for practical applications in astrophysics where a resolution below 15 eV is required to resolve satellite lines from highly ionized iron, such as He-like Fe XXV.

The STJs used for the present work have been fabricated by Oxford Instruments Scientific Research Division (Cambridge, UK). They are Ta–Al–AlO_x–Al–Ta multilayers deposited on polished sapphire substrates. The leads are 3 μm wide and made of niobium, in order to prevent diffusion of quasiparticles from the lower energy gap tantalum into the leads. The tantalum layer thicknesses for base and top electrodes are 110 and 95 nm, respectively. The aluminum layers are 5 nm thick on either side of the barrier. The base film tantalum is epitaxial, with a residual resistance ratio of 48, whereas the top electrode is polycrystalline. The AlO_x barrier has an estimated thickness of <1 nm and a resistance of $\sim2.5\times10^{-6}\ \Omega\,\mathrm{cm}^2$. The energy gap of the devices at the barrier, as derived from the current–voltage ($I-V$) curves and assuming equal gaps in top and base electrode, is $2\Delta=1.31$ meV, close to that of bulk Ta. Leakage current densities, as measured at $T=0.30$ K, are typically ∼30 fA/μm^2. The available device sizes range from 10×10 to 100×100 μm^2. The work described in this letter has been performed on a 100×100 μm^2 STJ.

The experiments have been performed in a ^{3}He cryostat at its base temperature of 0.30 K. A superconducting magnet provides the magnetic field of ∼8 mT required to suppress the STJ's Josephson current and Fiske steps. The x-ray

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TABLE I. Energy and relative strength of the individual lines in the Mn K complex.

Line	Energy (eV)	Relative strength
Mn $K_{\alpha 1}$	5898.75	100
Mn $K_{\alpha 2}$	5887.65	51
Mn $K_{\beta 1}$	6490.45	12
Mn $K_{\beta 3}$	6490.45	6
Mn $K_{\beta 5}$	6535.20	0.0053

source is a radioactive ^{55}Fe sample emitting the Mn K_α ($E = 5895$ eV) and K_β ($E = 6490$ eV) line complexes. The energy[11] and relative strength[12,13] of the individual lines of this complex are listed in Table I. About 5% of the photons incident on the detector are absorbed in each of the two electrodes, while 90% are absorbed in the underlying sapphire substrate. A collimating pinhole with a diameter of ~2 μm at a distance of ~60 μm from the detector chip is used to selectively illuminate a small fraction of the total detector area. The diameter of the illuminated spot in this configuration is estimated as 5–10 μm (FWHM). The pinhole is aligned to the center of the STJ at room temperature with an accuracy[14] of ± 3 μm. From previous experience with smaller STJs, the misalignment with respect to the center of the STJ after cooldown is estimated at <10 μm. The rate of events detected in either of the two electrodes is ~1 cts/min. A separate experiment on the same STJ without the collimating pinhole was performed in order to measure the detectors energy resolution in full illumination mode, thereby assessing the overall contribution from spatial nonuniformities.

The STJs are read-out with room temperature electronics, consisting of a charge sensitive preamplifier at ~1 m from the STJ, and a shaping stage. The total electronic noise of the combination of STJ and electronics can be measured as the width of the pulse height distribution from electronic pulser signals which are regularly fed into the electronics during data acquisition. For each detected photon the charge output, which corresponds to the total number of tunneled electrons $N(E) = \langle n \rangle N_0(E)$ and the rise time of the charge pulse, which corresponds to the decay time of the current pulse from the STJ, are stored on a PC.

The typical signal measured for a 5.9 keV x-ray photon absorbed in the base electrode is 1.4×10^8 tunneled electrons, corresponding to an average number of tunnel processes per initial quasiparticle $\langle n \rangle \approx 28$. The $1/e$ decay time of the pulses, as derived from the rise time of the pulses from the charge sensitive amplifier, is typically 20 μs. Variations of $\pm 10\%$ in measured charge and rise time occur between different cooldown cycles. The signal from the top electrode is usually within a few percent of the base electrode signal amplitude. The measured energy resolution in full illumination is $\Delta E \approx 56$ eV (FWHM) for the base electrode and slightly more for the top electrode. The noise level, as measured from the electronic pulser signal, is $\Delta E_{\rm noise} \approx 12$ eV (FWHM) in this measurement.

The spectrum obtained with the collimated source is shown in Fig. 1. The assignment of the peaks to top and base electrode is based on the difference of ~10% in the number of counts, which is in agreement with the thickness ratio of the electrodes. The measured ratio of the pulse heights for the Mn K_α and Mn K_β lines ($Q_\beta / Q_\alpha = 1.092$) is smaller than the ratio of the corresponding energies ($E_\beta / E_\alpha = 1.101$). This indicates some degree of energy nonlinearity in the detectors response, which is attributed to self-recombination of quasiparticles.[15] All derived energy resolutions have been corrected for this energy nonlinearity. The measured energy resolution (FWHM) for the base electrode Mn K_α line complex is $\Delta E = 22.0 \pm 2.0$ eV (see insert in Fig. 1), while the top polycrystalline Ta electrode gives 29 eV. However, when fitting the measured line profile to two Gaussians corresponding to Mn $K_{\alpha 1}$ and Mn $K_{\alpha 2}$, with their relative intensities and energy separation fixed to the values in Table I, the single line energy resolution for the base electrode is found as $\Delta E = 15.7 \pm 2.3$ eV. The noise level in this measurement is $\Delta E_{\rm noise} = 5.7$ eV. The estimated contribution from the statistical noise [Eq. (2)], using $\langle n \rangle = 28$, is $\Delta E_{\rm stat} = 6.9$ eV, and the natural linewidths[16,17] of the K_α lines are $\Delta E_{\rm nat} = 2-3$ eV. Therefore, the residual broadening of the single Mn $K_{\alpha 1}$ line, obtained after subtraction of electronic noise, natural linewidth, and statistical noise, is $\Delta E_{\rm res} = 12.5 \pm 2.0$ eV. This residual broadening seems too large to be explained simply by spatial variations over a $\leqslant 10$ μm spot near the center of the device, compared to the 56 eV resolution measured in full illumination of the 100×100 μm^2 STJ. However, it is estimated that fluctuations in the bias voltage, induced by the voltage noise of the input field effect transistor (FET) of the charge sensitive preamplifier might provide an additional contribution to the right order. Generally, the gain of the device depends on the applied bias voltage and thus, variations in the bias voltage will give rise to variations in the measured pulse height.

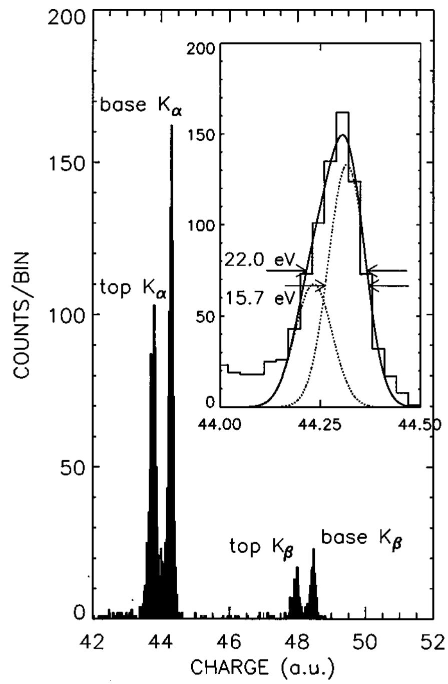

FIG. 1. Part of the pulse height spectrum from a 100×100 μm^2 STJ illuminated with a ^{55}Fe source emitting the Mn K_α ($E = 5.9$ keV) and Mn K_β ($E = 6.5$ keV) line complexes. The source is collimated to the center of the STJ. The insert shows the base electrode K_α line in detail. The solid line is the result of a least squares fit to two Gaussians representing the Mn $K_{\alpha 1}$ and Mn $K_{\alpha 2}$ (dashed lines).

In summary, by constraining the illuminated area of the detector to a small spot near the center, we have demonstrated the capability of STJs to operate at 5.9 keV photon energy with an energy resolution of 15.7 eV. This exceeds the limit set by statistical fluctuations and natural linewidth by only a factor of ∼2.

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