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THE DETECTION OF 6 keV X-RAYS WITH Nb JUNCTIONS

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Abstract

Refractory metal Nb/Al/Al-ox/Al/Nb junctions are shown to be sensitive to 6 keV X-rays over the temperature range from 2.8 to 1.4 Kelvin. For such junctions, having an observed minimum ionizing energy of 12 meV, a limiting energy resolution of 8 eV is predicted. Currently an energy resolution of 250 eV is observed at 1.4 Kelvin which is primarily dominated by system electronic noise. The Nb based junctions are shown to be very stable with respect to thermal cycling while their non-equilibrium physics can be simple scaled from the theory of Sn-junctions.

1. Introduction

X-Ray astrophysics deals with the study of highly energetic phenomena. Hot plasmas at temperatures of over a million degrees radiate the bulk of their energy at X-ray wavelengths. At temperatures of ~10^6- 10^7 K the X-ray emission arises mainly from a large number of K and L shell transition lines from elements ranging from Oxygen to Iron. At higher temperatures most of the low Z atoms are stripped of their electrons and a continuum spectrum dominates over the line emissions[1]. One important line complex remains dominant, however, that of Iron K emission around 6-7 keV. An energy resolution of below 15 eV is necessary to separate the many lines which arise in lower temperature plasmas or to resolve the resonance from the satellite lines. Such a capability provides for the detailed plasma diagnostics necessary to derive model independent data on temperatures, ionic abundances, electron densities etc. Non dispersive instruments such as gas scintillation proportional counters and solid state detectors, having energy resolutions at 6 keV of ~500 eV and 100 eV respectively, cannot provide this detailed type of information[2-3]. Dispersive devices, while achieving the desired resolution, suffer from low efficiency and a narrow energy range, which makes their application on the weak sources of cosmic X-ray emission limited. Superconducting tunneling junctions (STJ) and calorimeters can be used as medium resolution non-dispersive detectors of X-rays in the keV region[4-8]. Superconducting tunneling junctions offer the potential of a high energy resolution, broad band width, and possibly higher operating temperatures.

The reason that a detector based on a superconductor has the potential for high energy resolution is due to its small energy gap Δ which is of the order of meV. Basically, the energy deposited by the photo-absorbed X-ray produces an excess of quasiparticles in the superconducting films by breaking Cooper pairs. When operated in the Giaever mode, an additional quasiparticle current then flows across the thin insulating barrier of the tunneling junction, yielding a signal proportional to the X-ray energy. Theoretically, a Poisson statistics limited energy resolution of better than 10 eV FWHM could be expected for 6 keV X-rays.

Although junctions based on tin have demonstrated a good energy resolution (~45 eV), their practicality is limited due to their poor thermal recyclability and rather short device life time. These problems have been solved in the last few years for Niobium based junctions without reducing the required quality of the current - voltage characteristics[9-10]. In addition, the larger gap of Nb (Δ_{Nb} = 1.5 meV, Δ_{Sn} = 0.59meV) allows owing to the non-equilibrium theory of STJ detectors[11] an operating temperature higher by a factor of Δ_{Nb}/Δ_{Sn} ~3. Note, however, that a low operating temperature ($\Delta/kT \gg 1$) is still required to eliminate the recombination losses arising from thermally excited quasiparticles.

For applications in X-ray astrophysics however, which by necessity is performed using space-based platforms, a robust detector with an operating temperature higher than 1 Kelvin, allowing for simpler ^{4}He cryogenics, would be attractive.

2. Theory of STJ Detector

The theory for STJ detector has been developed recently[11] and we merely present the major temperature dependent behaviour. Basically, it is necessary to solve a set of rate equations relating to quasiparticles recombining and diffusing in the films and crossing the insulating barrier of the junction. The latter excess current produces the signal of the ionizing event. A simplified solution of the rate equations for the STJ detector leads to the following excess quasiparticle current:

$$i(t) = Qo\tau^{-1}_{tun}\exp(-(\tau^{-1}_{tun}+\tau^{-1}_{X}+\tau^{-1}_{R}(T))\cdot t)$$

where
τ_{tun} = tunneling time
$\tau_R(T) = \tau_0\sqrt{T}\exp(\Delta/kT)$: thermal recombination time
(τ_0(Nb) = 11 nsec)
τ_X: non-temperature dependent relaxation time
Qo : initial number of excess quasiparticles produced by absorption of X-ray.

By using a test pulse for calibration, the experimental results can be compared with theory by essentially calculating the integral of the excess current, which yields the temperature dependent accumulated charge:

$$Q(T) = Qo\,\frac{\tau^{-1}_{tun}}{\tau^{-1}_{tun} + \tau^{-1}_{R}(T\ ) + \tau^{-1}_{X}}$$

To operate a superconducting tunneling junction successfully as an X-ray detector with high energy resolution, the resistivity of the insulating barrier has to be as low as possible to collect the excess quasiparticles efficiently[6,11]. On the other hand, the subgap current has to be leakage free at the low operating temperature for a high dynamical resistance at the operating biasing voltage. This is important

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for a good signal to noise ratio in the applied charge sensitive circuitry[12-13].

3. Nb-junction Fabrication and I-V Curves

The Nb/Al/Al-ox/Al/Nb junctions used for this work were made using a variant of the SNEP method first developed by Gurvitch et al.[9] and subsequently adopted by numerous groups worldwide. The original Nb/Al/Al-ox/Al/Nb structures were deposited onto sapphire substrate during one pumpdown in a UHV DC magnetron getter sputter deposition system[10]. The devices were then isolated from this structure to yield eight square junctions with areas ranging from 10x10 μm^2 to 500 x 500 μm^2. In order to keep to a minimum any effects from quasiparticle diffusion into and out of the interconnection leads, the contact areas were kept as small as practicable, typically ~8 μm wide and 30 μm long. In this paper, two sets of devices are presented:

	thickness bottom Nb	thickness top Nb	oxide resistivity
Chip A :	350 nm	150 nm	$2.3.10^{-5}$ Ωcm^2
Chip B :	100 nm	200 nm	$0.3.10^{-5}$ Ωcm^2

The current leads were Au on chip A and Nb on chip B.

The current-voltage characteristics of a 20x20 $\mu m2$ Nb/Al/Al-ox/Al/Nb junction from chip A at a temperature of 2.17K is shown in figure 1. The normal conducting resistance was 7.2Ω while the dynamical resistance is larger than 10 kΩ (for a complete discussion of the I-V characteristics see e.g. ref [6]).

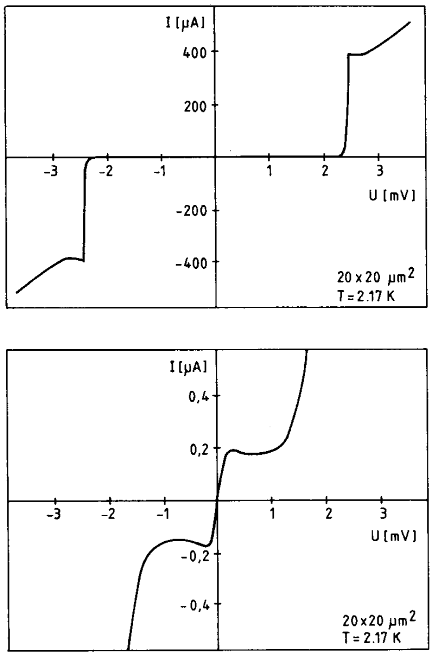

Figure 1. The current voltage characteristics of a 20x20 μm^2 Nb/Al/Al-Ox/Al/Nb junction at T = 2.17 Kelvin.

4. Experimental Results

The ^{55}Fe spectra obtained from three junctions on chip B, all of different sizes, are illustrated in figure 2. The charge collected from the three junctions was ~5.10^5 electrons leading to a minimum ionizing energy of ~12 meV. The best observed energy resolution was found however to be ~250 eV FWHM for the 10x10 $\mu m2$ junction (Figure 2a). This resolution is dominated primarily by the system electronic noise, since the resolution degrades as the device area becomes larger owing to the decreases in the impedance (c.f. figure 2c) where the MnKα and Kβ lines are not resolved).

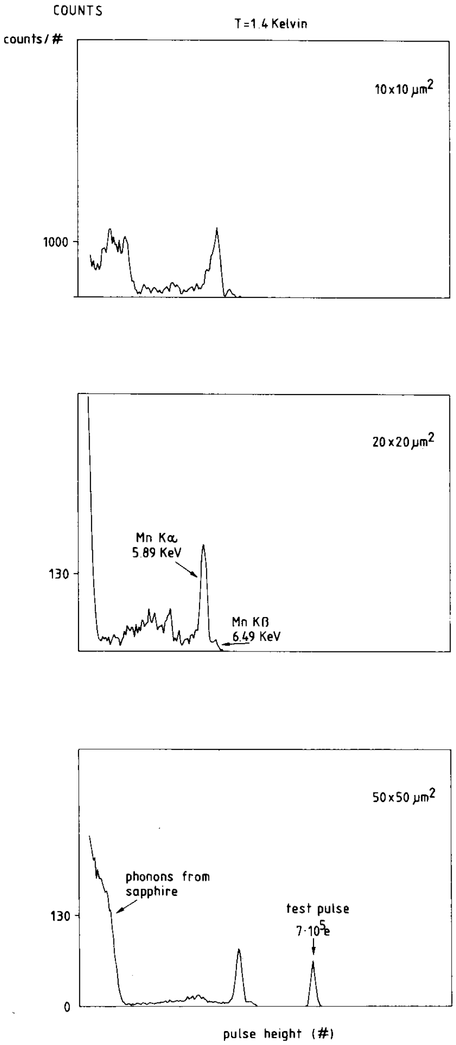

Figure 2. The pulse height spectra of an ^{55}Fe (MnKα = 5.89 keV, Mn Kβ = 6.49 keV). X-ray source for three different sized junctions on chip B at T = 1.4 Kelvin.

At about 20% of the MnKα peak a structure appears in the spectrum which can be interpreted as due to 2Δ phonons originating from 6 keV X-rays absorbed in the sapphire substrate. This crystaline substrate allows energetic phonons (possibly ballistic) to have rather long life-times at these low temperatures. Clearly such junctions could be utilized as phonon sensors on larger volume crystal detectors (see ref [14] and references therein). The temperature dependence of the Nb-junction detector has been determined and compared with the predictions of the non-equilibrium theory as illustrated in figure 3.

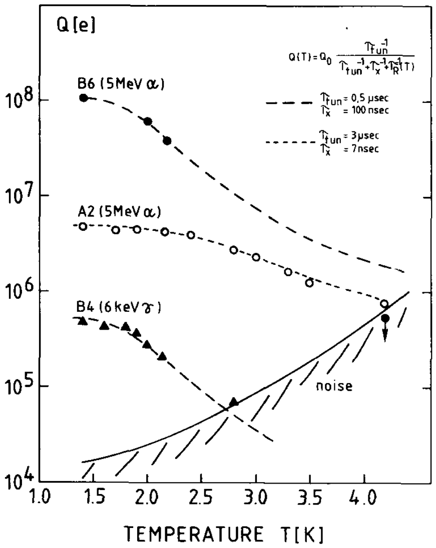

Figure 3. The temperature dependence of signal pulse heights from a ^{241}Am α source and a ^{55}Fe X-ray source from junctions on chip A and B. The theoretical predictions from the non-equilibrium model is also shown.

With junction A2 no X-rays were seen, only measurements with the 5 MeV particle from the ^{241}Am source could be made. At 4.2 K the α signals from junction B6 were barely above the noise level. The first X-ray signals appear in junction B4 at 2.8 K. The results of the measurements and the comparison with theory are summarized in the following table:

Junction	Area	Source	τ_{tun}	Q_0	τ_X
A2	100x100 μm^2	241Am	3 μsec	2.10^8	7 nsec
B6	50x50 μm^2	241Am	0,5 μsec	7.10^8	100 nsec
B4	20x20 μm^2	55Fe	0,5 μsec	3.10^6	100 nsec

We have improved the performance of the detectors on chip B by increasing the ratio of τ_X/τ_{tun} by a factor of 85.

From figure 2(c) an efficiency of ~20% for X-rays absorbed in the substrate can be determined. This, coupled to the measured ratio of Qo in junctions B6 and B4, leads to an energy calibration of 6.6 MeV for the α particle signal observed in junction B6. This demonstrates that this signal originates from the 5 MeV particles absorbed in the sapphire substrate. The value of Qo = 3.10^6 electrons for the case of the X-ray data yields an intrinsic minimum ionizing energy E of ~2 meV, rather close to the band gap value for Niobium.

5. Conclusion

6 keV X-rays have been detected with thermally recyclable Nb-junctions in the temperature range 1.4 K to 2.8 K. The temperature dependence of the signal pulse height can be successfully described by the non-equilibrium model of the STJ detector. The minimal ionizing energy of the Nb-junction detector is of the order of the superconducting gap of Nb. This suggests a Poisson statistics limited resolution of better than 10 eV at 6 keV. The best observed FWHM resolution of 250 eV is primarily limited by electronic noise. Storable and thermally recyclable STJ-detectors make it now possible to study more systematically this potential detector. These encouraging preliminary results indicate that on-chip arrays having a broad band pass and good energy resolution should be feasible to construct. Such an array when placed in the focal plane of an X-ray imaging telescope would be a powerful tool for X-ray astrophysics.

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