Bulletin de la Société Royale des Sciences de Liège, Vol. 74, 5-6, 2005

High Q Niobium superconducting resonators for use as Kinetic Inductance sensing elements

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Abstract: One of the greatest challenges in the development of future space based instruments for sub-mm astronomy is the fabrication of very sensitive and large detector arrays. Within this context we have started the development of Microwave Kinetic Inductance Detectors (MKID's). The heart of each detector consists of a high Q superconducting quarter wavelength microwave resonator. As a result it is easy to multiplex the readout by frequency division multiplexing. The flexibilty of the MKID allows for radiation detecting from the sub-mm to the X ray by choosing a suitable radiation absorber or antenna. The predicted sensitivity of the MKID is below $NEP \sim 1 \cdot 10^{-20} W/\sqrt{Hz}$, low enough for any envisionable application in the sub-mm, optical and X ray wavelength ranges. We describe our initial experiments with these resonators, made of 100 nm Nb films on a high purity Si substrate. We measure the Q factors of several resonators using a vector network analyzer and find Q factors up to 90.000, limited by the intrinsic quality of the Nb resonator.

1 Introduction

The science themes for future Far-InfraRed (FIR) and sub-mm astronomy are the emergence and evolution of stars and galaxies, and the birth of stars and planetary systems (see *Community Plan for Far-Infrared/Submillimeter Space Astronomy* (2002)). The instrument of choice to address these science themes will be a space based telescope with high spatial resolution, high observation speed and background limited sensitivity. High spatial resolution implies a larger mirror or interferometry by formation flying of several telescopes. High speed is accomplished by using large (100 x 100 pixels or more) detector arrays. Background limited sensitivity can be achieved by reducing the instrumental background noise significantly, which is only possible with actively cooled (<10 K) telescopes. Only in that case the sky background limited photon noise can be reached, at a $NEP \sim 1 \cdot 10^{-20} W/\sqrt{Hz}$ for spectroscopy with a resolving power R $\sim$ 1000. No practical detector array exists to date with a $NEP < 1 \cdot 10^{-17} W/\sqrt{Hz}$. Furthermore, existing detector systems are difficult to multiplex, leading to very complex instruments.

Within this context we have started the development of Microwave Kinetic Inductance Detectors (MKIDs) (see P.Day *et al.* (2003) and B. Mazin (2004)). The MKID is a new detector design based upon a superconducting resonance circuit that can be used in combination with a suitable radiation absorber or antenna to detect radiation from the sub-mm range (at a frequency of $\sim$ 100 GHz, corresponding to a wavelength of 3 mm and a photon energy of 0.4 meV) to the X ray (at photon energies of several keV).

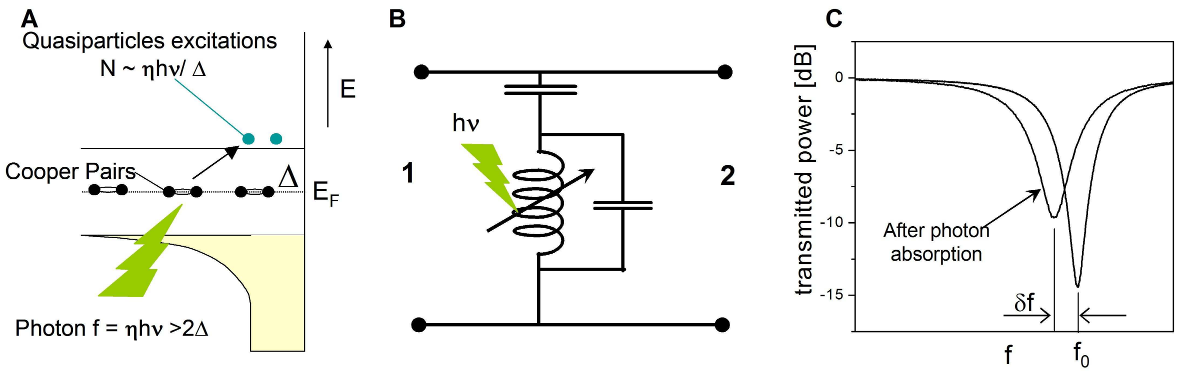

Figure 1: Principle of the MKID operation. Panel **A** shows the semiconductor representation of a superconductor, showing the Cooper pairs as paired particles at the Femi level E_f and the quasiparticles as single quasiparticles at energies Δ (the superconducting energy gap) above the Fermi level. A photon with energy $h\nu > 2\Delta$ can be absorbed by the Cooper pairs with as a result an increase in the number of quasiparticles at energies close to Δ (and identical reduction in Cooper pairs). The change in Cooper pair number results in a change in complex surface impedance of the superconductor. By making the superconductor part of a resonance circuit, as shown in Panel **B**, we change the complex impedance of the resonance circuit and with that the resonance feature. In this case the superconductor is coupled capacitively to a through line, with the result that it will form a short circuit at resonance. A measurement of the transmitted power from contact 1 to contact 2 shows dip at resonance this is shown in Panel **C**. The absorption of a photon reduces the resonance frequency (due to the reduction in Cooper pairs) and the dip depth (due to the increase in quasiparticle number).

A MKID is a superconducting pair breaking detector, i.e. it senses the change in the number of Cooper pairs due to the absorption of radiation incident on the superconductor. This is done by means of a measurement of the complex surface impedance of the superconductor

$$Z_s = R_s + i\omega L_s \tag{1}$$

where R_s is a resistive term, to be associated with the quasiparticles, and L_s the kinetic inductance due to the Cooper pairs. This is illustrated in Fig. 1, where we give the semiconductor representation of a superconducting material at very low temperatures. The Cooper pairs are represented as paired particles at the Fermi energy E_f, the quasiparticles are represented as single particles at energies $E \geq E_f + \Delta$, where Δ is the energy gap of the superconductor. A photon with an energy $h\nu > 2\Delta$ incident on the superconducting film can be absorbed by breaking up Cooper pairs and creating a number of quasiparticle excitations $N_{qp} = \eta h\nu/\Delta$, with η the efficiency of creating quasiparticles. As a consequence both L_s and R_s change due to the photon absorption. The resulting change in surface impedance is read out by making the superconducting film part of a resonant circuit, capacitively coupled to a through line, as depicted in Panel B. The change in surface impedance is indicated by the variable inductor, since at low temperatures $\omega L_s >> R_s$. If the circuit is at resonance it short circuits the through line with the result that we observe a strong decrease in transmitted power from contact 1 to 2. This is indicated in Panel C. The absorption of a photon will cause the resonance center frequency to shift to lower values (due to the increase in L_s) and to make the measured dip in the transmission smaller (due the increase in R_s). Both effects together produce a phase change at the original resonance frequency f_0. This phase change as a function of quasiparticle number is the signal we read out to measure the absorption of a photon.

2 MKID design

For use in a radiation detector array each pixel of the MKID would consist of suitable antenna or absorber, coupled to a superconducting resonator. The resonator consists of a superconducting coplanar waveguide (CPW) with a length of $\frac{1}{4}\lambda$, where λ is the wavelength corresponding to the resonance frequency. A scanning electron microscope picture is given in in Fig. 2[1]. In the $\frac{1}{4}\lambda$ resonator the central conductor is shorted at the far end to the ground plane and floating at the coupler end, where it is coupled capacitively to the through line by letting it run parallel with it. The length of the coupler (and the distance between the through line and the part of the resonator running parallel with it) determines the coupling Q of the resonator Q_c. The entire structure is acts a capacatively coupled resonator. The responsivity is defined as the phase change per quasiparticle added to the central line of the resonator $S_\theta = \gamma\alpha Q/V$, with Q is the resonator quality factor, V its volume, α the kinetic inductance fraction and γ a material and frequency dependent constant (see P.Day *et al.*(2003), B. Mazin (2004) and A. Porch (2005)). The key to the operation of the MKID is the fact that the Q factor of the superconductor is determined by the ration of the imaginary and real part of the complex surface inductance, which increases exponentially with decreasing temperature. Hence the responsivity will also increase exponentially with decreasing temperature.

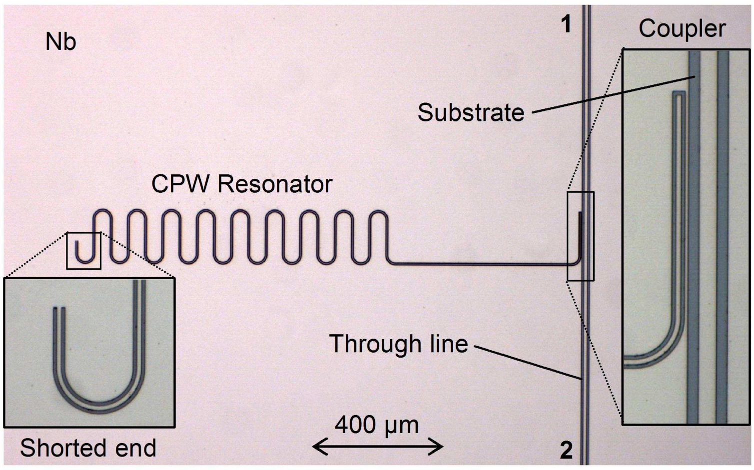

Figure 2: Scanning electron microscope picture of a Coplanar waveguide based Nb resonator on a Si substrate. The bright areas correspond to the 100 nm Nb film on top of the Si, the dark areas correspond to bare Si substarte. The coupling capacity of the $1/4\lambda$ long resonanator is formed by the coupler, where the through line and resonator run parallel.

[1]A CPW is a planar structure consisting of a central conductor and a ground plane at both sides

The fundamental noise in the system, is given by the fluctuation in quasiparticle number. This generation-recombination noise can be written as:

$$NEP_{gr} = 2\Delta\sqrt{N_{eq}/\tau_{qp}} \tag{2}$$

with Δ the energy gap, N_{eq} the equilibrium number of quasiparticles and τ_{qp} the quasiparticle lifetime. Since both N_{eq} and $1/\tau_{qp}$ decrease with temperature according to the Boltzmann Factor $exp(\frac{-\Delta}{kT})$, so does the generation recombination noise. Considering, as an example, a 100 nm thick Al resonator with a 1 μm nm wide central line at 6 GHz. Such a device has a length of about 5 mm, a volume of 500 μm^3 and $\alpha \sim 0.2$. The calculated NEP decreases to values below $NEP = 1{\cdot}10^{-20}$ W/$\sqrt{Hz}$ at temperatures below 1/10 of the critical temperature of Al, 110 mK. The responsivity of this resonator would be about 0.004 degree/quasiparticle. The phase noise of a cryogenic, ultra low noise microwave amplifier ($T_n \sim 4K$), such as a InP based MMIC (see N. wadefalk *et al.*, (2005)), is of the same order when the signal is integrated over a time $\tau \approx 50\mu$sec, which is the response time of the resonator discussed here, $\tau = Q/\pi\nu_{res} \approx 50\mu$sec. Hence the whole detector could in principle be limited by its fundamental noise and not by the noise of the external amplifier. In practice however P.Day *et al.*(2003) and B. Mazin (2004) have found the phase noise of similar detectors to be much greater, yielding a $NEP \sim 1{\cdot}10^{-17}$.

A part from the quasiparticle recombination noise any pair breaking radiation detector has an additional fundamental limit to its sensitivity caused by the intrinsic quasiparticle creation statistics due to the photon absorbtion. This Fano limit arises because the creation of (many) quasiparticles from a single (high energy) photon is a noisy process. The maximum energy resolution δE due to the Fano limit is given by:

$$\delta E = \sqrt{4\,ln4} \cdot \sqrt{\epsilon\, E\, F} \tag{3}$$

with E the energy of the incoming photon, $\epsilon = 1.4{\cdot}\Delta$ the engy required to create 1 quasiparticle and F the fano factor. The relation between the Fano limited δE and the corresponding NEP of the detector is given by

$$NEP \approx \frac{\delta E}{\sqrt{4\ln 4} \cdot \sqrt{\tau}} \tag{4}$$

with τ the integration time, which for a MKID can be taken as the response time of the resonator.

For a practical receiver radiation has to be coupled to the central line of the MKID resonator. However, the geometry of the resonator is not suitable as a direct radiation absorber. As a consequence it is advantageous to use an additional superconducting absorber (or antenna) to absorb the radiation. The radiation will break Cooper pairs in the absorber, and the resulting quasiparticles should than be transported to the central line of the MKID resonator. This is achieved by using a superconductor with a high critical temperature as absorber and a superconductor with a low critical temperature as the resonator. A good candidate would be a Al MKID resonator coupled to a Ta abosorber. Quasiparticles created in the Ta absorber will diffuse due to their random motion, eventually ending up in the Al resonator, which is galvanically coupled to the Ta absorber. Once in the Aluminum the quasiparticles will cool quickly to the (lower) gap energy of the Al, emitting a phonon. As a result they are trapped inside the Al and can be detected. If we would combine the Ta absorber with an Al resonator we will have a detector with an energy resolution determined by the Fano limit of Ta with $\Delta = 0.68$ meV. For an optical photon at 1 eV (corresponding to $\lambda = 1.2\mu m$) incident on a Ta absorber we get

$\delta E = 36.5$ meV ($E/\delta E = 27$). The Al resonator should therefore have a $NEP < 3.5 \cdot 10^{-19}$ W/$\sqrt{Hz}$ to form a Fano limited detector in this wavelength band. At even lower photon energies the NEP of the MKID will be the limited factor. At higher photon energies the Fano limit increases, resulting in less stringent demands for the resonator NEP. However, the saturation energy of the MKID resonator should be high enough to prevent saturation at the absorption of high energy (X ray) photons.

A very important and useful feature of the MKID is the fact that it is, by design, very easy to multiplex the read-out using frequency division multiplexing. This can be understood by looking at the resonator geometry as depicted in Fig. 2 which has a response as depicted in Panel C of Fig. 1. The resonance frequency of the resonator is determined by the length of the resonator CPW, and the bandwidth of the resonance feature is determined by the Q factor. A Q factor of $1 \cdot 10^6$ would enable more than 10.000 resonators in a 1 GHz bandwidth. Moreover, Mazin et al. (2005) have proposed recently a digital read out of many KID's using software defined radio, offering a relatively simple and cheap solution to the room temperature read out of many pixels.

3 Experiments

For a suitable MKID detector one should use, for the resonator, a superconductor with a low critical temperature Tc and a long quasiparticle lifetime, such as Al. However, as a first step, we have started with measurements of Nb based resonators. The latter material is not suitable for real detectors because of its high Tc. But, it offers the advantage to quickly evaluate our resonator design and test setup. We use a 3He sorption cooler mounted inside a 4He vacuum cryostat as cryogenic system, achieving a base temperature of 290 mK, which is far below 1/10 of the critical temperature of the Nb films (9.0 K). At the cold stage of the 3He cooler we mount a specially designed copper holder with 2 microwave launchers with SMA connectors. The central conductor of each launcher is soldered to the central strip of a copper CPW on top of a Duroid TMM board. The board is used to form the transition between the launcher and the KID chip and is designed using the commercial software package SONNET. It forms the transition from a grounded CPW at the launcher connection to an ungrounded CPW at the chip end. Connections to the CPW on the chip are made using several bond wires, additionally there are bond wires from the chip ground plane to the holder to prevent unwanted resonances. Stainless steel coax cables are used from room temperature to the 4.2 K plate of the 4He cryostat. From there we use a strapped Al coaxial cable, a strapped 20 dB attenuator, and 10 cm of stainless steel coaxial cable to reach the short copper coax cables connected to the holder. The hold time of the sorption cooler with the holder on top and all coax cables connected is in excess of 6 hours at 290 mK. A commercial Miteq amplifier, with a practical bandwidth from 1-10 GHz is used at room temperature to boost the signal, enabling faster measurements.

We measure the fraction of the transmitted power, denoted by S21, as a function of frequency using a Agilent PNA-L vector network analyzer. This is done for three different chips containing 1-4 resonators each from 2 different batches (D1 and D2). The inset of Fig 3 shows the measured transmission of the whole setup in a 1-10 GHz band, which indicates that our RF design is adequate within the 10 GHz bandwidth of our amplifier. The measured resonance dips for a set of KID resonators are given in Fig. 3 as well. We apply a microwave power of -60 dBm at the resonator and notice that at higher powers the resonance feature starts to deform. From the measured S21 data we can obtain the total Q factor of the resonator using $Q = f_0/\delta f$, with

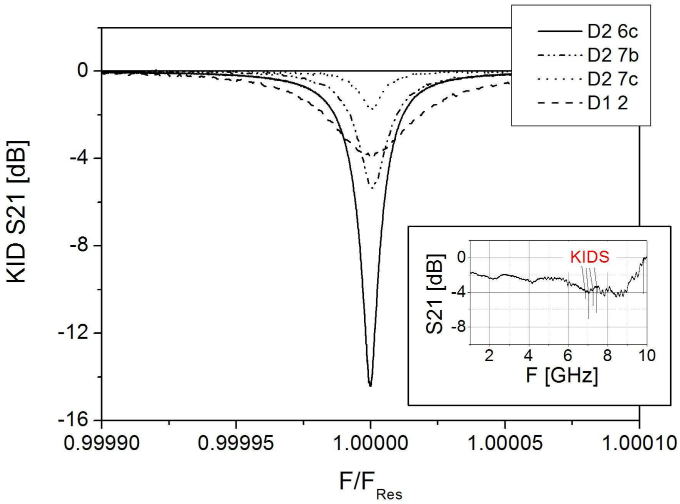

Figure 3: Measured transmission normalized to the KID resonator center frequency for several KID's. The inset shows the full bandwidth of the experimental setup.

f_0 the resonance frequency and δf the frequency span between the two points at which

$$|S_{21}|^2 = \frac{|S_{21}^{min}|^2 + 1}{2} \tag{5}$$

with S_{21}^{min} the minimum transmission (at resonance). Assuming that the total Q is the combination of the coupling Q, Q_c, (defined by the coupling between the resonator and the through line) and the intrinsic Q of the superconducting resonator, Q_i we have $1/Q = 1/Q_i + 1/Q_C$. The relation between Q_i and Q is given by $Q_i = Q/S_{21}^{min}$. From these equations it follows that we expect that the measured Q is identical to Q_c and that we see a very deep dip at resonance in $S21$, if the intrinsic quality of the resonator is much larger than Q_c. If Q_i becomes smaller we expect to see a more shallow resonance feature and a decrease in measured Q. The design value of Q_c, as well as the measured values of Q_i, Q and the resonance frequency of each resonator are listed in Table I. The highest measured Q-factor is obtained from device D2-7c, Q=89.000. This value is far below the designed value of Q_c. This is caused by the low value of Q_i, directly visible from the shallow depth of the resonance feature shown in Fig. 3. We also find that the measured value of Q_c is lower than the designed value. A similar observation can be made for device D2-7b. Device D2-6c has a Q factor much closer to the design Q, with a much lower S21 at resonance, and thus a higher Q_i. Longer resonators designed around 1 GHz show, therefore, a lower intrinsic quality factor, than shorter resonators designed around 7 GHz. Radiation losses cannot account for the observed behavior, because the radiation Q factor increases with the resonator length squared (see Mazin (2005)). Hence the observed behavior might be related to any length dependent parasitic loss term in the Nb film. Device D1-2, made in another batch, characterized by a poor Nb quality with a resonator Tc of 4 K, has an even lower Q_i.

	Design Q_c	Measured Q	measured Q_i
D2-7c	900.000	89.000	110.000
D2-6c	100.000	51.000	270.000
D2-7b	200.000	58.000	111.000
D1-2	100.000	21.000	34.000

Table 1: Table I: Measured Q's design Q_c's and Q_i's of the resonators.

4 Conclusions

MKID's are a very promising detector concept for a great variety of wavelengths, ranging from the sub-mm to the X ray. The advantages are easy multiplexing of the readout using frequency division multiplexing at GHz frequencies and a high predicted sensitivity. We have presented initial results on 2 batches of Nb resonators made on Si substrates. We find that our microwave design allows measurements in a bandwidth from 1-10 GHz without any spurious resonances, indicating that the experimental setup is adequate. In the Nb resonators we find Q factors up to 90.000, good enough already for many applications. The measured Q values are found to be limited by the intrinsic quality of the resonators themselves. The latter can be caused by either the Nb film or the substrate. It is to be expected that material and substrate optimisation will result in even higher Q factors for similar systems.

Acknowledgements

This work was partially supported by Radionet and the VENI program of NWO. The authors wish to thank P. de Korte for support and very fruitful discussions

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