ORAL SESSION n°8

« Superconductors for Imagers & Detectors »

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Dr. Netty Honish & Dr. Jacob Kooï

Development of High-Q Superconducting Resonators for use as Kinetic Inductance Detectors

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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 sensitive and large detector arrays. Within this context we have started the development of Microwave Kinetic Inductance Detectors (MKIDs). 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 flexibility of the MKID allows for radiation detection from sub-mm to X ray by choosing a suitable radiation absorber or antenna. The predicted sensitivity of the MKID is below NEP ~ $1 \cdot 10^{-20}$ W/√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 50000, limited by the intrinsic quality of the resonators. We furthermore obtain the responsivity of these resonators, with values up to 0.08 radians per 10^6 quasiparticles.**

I. 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 [1]. The instrument of choice to address these science themes will be a space based telescopes with high spatial resolution, high observation speed and background limited sensitivity. High speed is accomplished by using large (100 x 100 pixels or more) detector arrays. High spatial resolution implies a larger mirror or interferometry by formation flying of several telescopes. 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 can the sky background limited photon noise be reached, at a NEP ≈ 10^{-20} W/√Hz for spectroscopy with a resolving power R ~ 1000. No practical detector array exists to date with a NEP < 10^{-17} W/√Hz.

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Within this context we have started the development of Microwave Kinetic Inductance Detectors (MKIDs) [2]. For use in a sub-mm or FIR detector array each pixel of the MKID would consist of an antenna or absorber, coupled to a high Q ¼λ Coplanar waveguide (CPW) microwave resonator. This resonator is coupled capacitively to a through line, which enables easy frequency division multiplexing of many resonators at slightly different frequencies. A picture of such a resonator with a through line but without any absorber or antenna, is shown in Fig. 1. At resonance the resonator acts as a short, with the result a strong reduction in the transmission measured from contact 1 to contact 2, S_{21} (indicated in Fig. 1). The principle of operation is as follows: Radiation that is coupled to the resonator at a frequency $h\nu>2\Delta$ will break up Cooper pairs in the central superconducting strip of the resonator. The reduction in Cooper pair density gives rise to a reduction in the kinetic inductance L_K, causing a shift in resonance frequency. When used as a radiation detector one measures the phase of the signal transmitted from contact 1 to 2 exactly at the resonance frequency. Here the absorption of a photon causes a change in the transmitted phase proportional to $\alpha Q/V$, with Q is the resonator quality factor, V its volume α the kinetic inductance fraction [2,4,5]. Using a high Q resonator with a limited film thickness in combination with a low noise microwave amplifier, such as a InP based MMIC

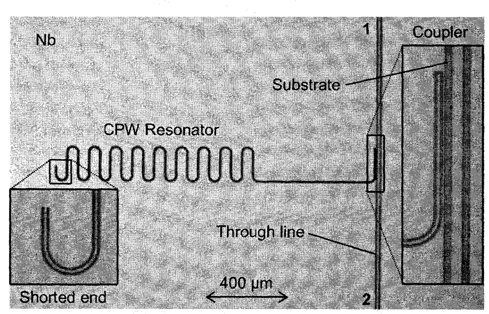

Fig.1: Scanning electron microscope picture of a Coplanar waveguide based Nb resonator on a Si substrate. The bright areas correspond to the 100 nm Nb film on top of the Si, the dark areas correspond to bare Si substrate. The coupling capacity of the 1/4λlong resonator is formed by the coupler, where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

[3], enables, in principle, the detection of a single quasiparticle. The detector noise is, in theory, limited by the fundamental quasiparticle generation-recombination noise, enabling (in theory) sensitivities as low as NEP < 10^{-20} W/$\sqrt{Hz}$ at temperatures below 1/10 of the critical temperature of the superconductor [2,4,5]. Multiplexing of many pixels is done in the frequency domain, where every pixel (i.e. antenna or absorber) is coupled to a different resonator coupled to the same through line. By changing the length of every resonator slightly all resonators will have different resonant frequencies. A 2 μm length difference between the resonators would allow 2000 resonators in a 1 Ghz bandwidth around 7 GHz (where the resonator length is about 4 mm on a Si substrate with ε=11.8). The readout of the phase transmitted at each resonator can be done using only room temperature electronics (for details see Ref.[6]). The cryogenics will be limited to 2 coaxial cables to the sample holder and 1 microwave amplifier at about 4K. 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 Nb KID's are not suitable for real detectors because of its high Tc and short quasiparticle lifetimes (see [2]). But, they offer the advantage to quickly evaluate our resonator design and test setup.

II. Experiment

The resonators are fabricated using DC sputter deposition of a 100 nm Nb layer on top of a N doped Si <100> substrate with a resistivity in excess of 1 kΩcm. The KID patterns are subsequently defined using e-beam lithography and dry etching. We use a 3He sorption cooler mounted inside a liquid He vacuum cryostat as cryogenic system, achieving a base temperature of 300 mK, which is far below 1/10 of the critical temperature of the Nb films. At the cold stage of the 3He cooler we mount a specially designed copper sample holder. The holder has 2 microwave launchers that have a SMA connector at one side and a small pin at the other, which is soldered to the central strip of a copper CPW on top of a circuit board made of Duroid 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. With careful mounting of the chip the setup has a resonance free bandwidth of 9 GHz [7]. Stainless steel coax cables are used from room temperature to the 4.2 K plate of the 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 at 300 mK. The hold time of the sorption cooler with the holder on top and all coax cables connected is in excess of 6 hours at 300 mK. A commercial room temperature Miteq amplifier, with a practical bandwidth from 1-10 GHz and a noise temperature of about 150 K, is used at room temperature to boost the signal, enabling faster measurements. We measure the fraction of the transmitted power, denoted by S_{21}, as a function of frequency and temperature using a Agilent PNA-L vector network analyzer. A Labview program is written to automatically measure many KID's in one single cool down as a function of temperature. Fig. 3A gives the measured resonance curves between 3.3 K and 300 mK for one of the Nb resonators. The dots indicate the resonance frequency. The high temperature data corresponds to the left most resonance dip, the lowest temperature to the rightmost resonance dip. It is obvious from the figure that the resonance frequency and Q factor increase with temperature. The Q factor is given by, $Q=f_{res}/2\delta f$, where the resonator bandwidth δf is defined by the difference between the two frequency points where $S_{21}= \frac{1}{2}(S_{21,min}+1)$. Since we can model every resonator as the series combination of a coupler with Q_C the coupling Q and the resonator itself, with Q_i the intrinsic Q. we can obtain from the measured Q factor and $S_{21,min}$ Q, Qi and Qc using $Q=Q_CQ_i/(Q_i+Q_C)$ and the fact that $Q_i=Q/S_{21,min}$ [4]. The temperature dependencies of these three parameters are given in Fig.3 B. The line through the datapoints of the measured Q_i is a calculation of the Q factor using Mattis-Bardeen theory, using a Kinetic Inductance fraction as a fit parameter [3,8] and limiting the Q_i to the experimentally obtained maximum

	Design parameters			Measured parameters at low temperature						
ID	L [mm]	F_0 [Ghz]	Qc	T [K]	F_0 [GHz]	Q [$\cdot 10^5$]	Q_c [$\cdot 10^5$]	Q_i [$\cdot 10^5$]	$S21_{min}$ [dB]	$\delta\theta/dN_{qp}$ rad/10^6qp
6a	4.101	7.2	$1 \cdot 10^5$	0.65157	6.8623	0.36246	0.49329	1.3666	-11.479	0.06
6b	3.990	7.4	$1 \cdot 10^5$	0.6476	7.0292	0.48569	0.66597	1.7942	-11.333	0.077
6c	3.885	7.6	$1 \cdot 10^5$	0.64359	7.2445	0.43671	0.82485	0.9280	-6.5331	0.056
6d	3.786	7.8	$4 \cdot 10^4$	0.63979	7.4148	0.21658	0.27531	1.0153	-13.372	0.031
9a	4.101	7.2	10^3	0.578	6.851	0.0248	0.0286	0.215	-18.8	0.0003
9b	3.990	7.4	$4 \cdot 10^4$	0.581	7.046	0.2468	0.315	1.14	-13.3	0.02
9c	3.885	7.6	$2 \cdot 10^5$	0.579	7.361	0.170	0.939	0.207	-1.7	0.04

Table 1: Measured parameters at low temperature (the temperature is given at colum T) for several Nb KID resonators fabricated on a <100> Si sunstrate.

value. We find a kinetic inductance fraction of 0.2, in reasonable agreement with a direct calculation giving 0.26. Note that the coupling Q is constant with temperature as expected over this range. The resonance dips shown in Fig. 3A can be plotted as well in the complex plane, as in Fig. 3C, where the frequency increases clockwise around the circle. When operated as a radiation detector the KID measures the phase change at the resonance frequency due to the quasiparticles created by the radiation absorption. In this measurement we create the quasiparticles by increasing the temperature. In Fig. 3C the black dots indicate the resonance frequency at 300 mK on the resonance circles at other temperatures. The phase response of the resonator can be obtained by measuring the (phase) angle between the location of the 300 mK resonance frequency on the 300 mK circle and the location of the same frequency in the resonance circles at other temperatures. The centre of the resonance circle at 300 mK is taken as the origin. This procedure is indicated by the arrow in Fig. 3C and the result is plotted in Fig. 3 D. The resonator shows a very steep phase response between 1.5 and 2.5 K. At higher temperatures the phase change saturates, and at low temperatures the phase change shows a non-monotonic behaviour, which we attribute to a substrate effect and not to a change in quasiparticle density. We take the positive phase change with temperature and convert the temperature scale to quasiparticle density using:

(1)

with N_0 the single spin density of states at the Fermi level ($1.3 \cdot 10^{11}$ $eV^{-1}\mu m^{-3}$ for Nb [8]). Numerically differentiating the phase change with respect to quasiparticle number gives now the responsivity in radians per quasiparticle for our resonators. Results from several resonators are given in Table 1. From the table several conclusions can be drawn. First, the resonance frequencies are lower than calculated, this can be attributed to the fact that in the design we did not take into account the kinetic inductance, which reduces the resonance frequency. A similar effect (or opposite in sign) can be observed if the CPW dimensions differ from the design values, which is not likely given the fact that the resolution of our e-beam lithographic process is of the order of 50 nm. Furthermore the intrinsic Q factor is limited to about 100.000 and not frequency dependent. This value is roughly 5 times lower than reported

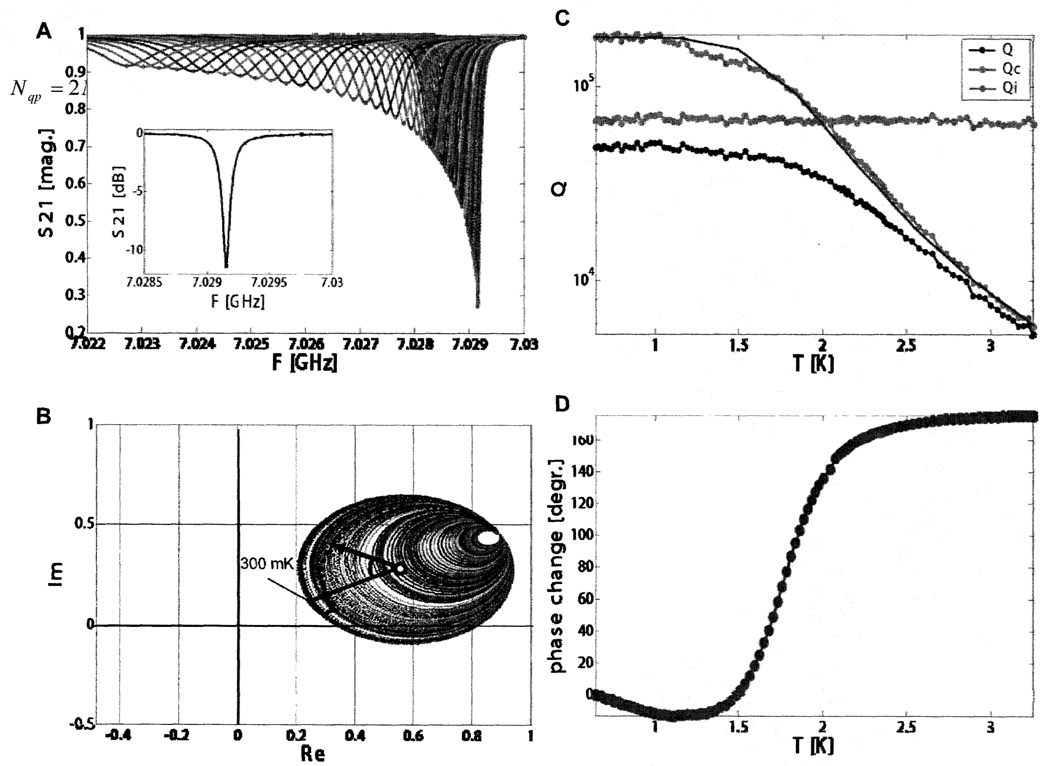

Fig.2: **A**: Measured transmission around the resonance frequency of one of the resonators for different temperatures between 3.3 K(left) and 0.3 K (right). the insert shows the 300 mK resonance feature over a smaller frequency range. **B**: Q factors obtained from the data shown in panel A. Q is the measured Q factor of the resonance dip, Qc the coupling Q factor and Qi the intrinsic Q factor of the resonator. The line is a theoretical calculation using the kinetic inductance fraction as a fit parameter. **C**: The data plotted in A in the complex plane, the dots represent the 300 mK resonance frequency at higher temperatures. the arrow indicates how he phase can be measured as a function of temperature. **D**: The phase change as a function of temperature as illustrated in C.

for Al resonators on Si [3] but comparable to results of Al on Sapphire [3]. Since we do not observe any dependence of Q_i with resonator length we can exclude radiative losses due to the substrate as the limiting factor. Possibly an excess surface resistance of the Nb films limits the Q factor. Furthermore, the coupling Q is roughly half the designed value which is not understood. The responsivities as shown in the last column are comparable to those of Al resonators [4] with similar Q factors and scale roughly linear with the measured Q factor as expected, since the device volumes quoted here are almost identical.

III. CONCLUSION

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 50.000, good enough already for many applictaions. 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.

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