Quasiparticle lifetime in tantalum kinetic inductance detectors

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The quasiparticle lifetime is a crucial parameter in achieving a background limited noise equivalent power for kinetic inductance detectors. We present measurements of the quasiparticle lifetime of 150 nm thick sputtered tantalum on silicon kinetic inductance detectors using optical pulses. We find that the quasiparticle lifetime saturates at low temperatures, increases to a maximum of up to 45 μs and subsequently drops with increasing temperature. We attribute this behavior to non-uniformity in the superconductor.

Introduction

One of the greatest challenges for far infrared astronomy is the development of sensitive large cameras ($>10^4$ pixels), having a background limited sensitivity. To date no such detector exists. Recently kinetic inductance detectors (KIDs) have been proposed [1].

A KID consists of a superconducting microwave resonator and is a pair breaking detector; incident radiation breaks Cooper pairs into quasiparticles, changing the kinetic inductance of the superconductor, and thus the resonance frequency [2,3] and phase of the forward transmission.

This non-equilibrium process leads to an excess amount of quasiparticles above the superconducting gap depending on the rate of photon absorption and quasiparticle loss. The interplay between photon absorption, quasiparticle recombination, phonon trapping and local superconducting properties leads to an effective 'lifetime' of the quasiparticles [4,5]. The detectivity of KIDs and other pair breaking detectors such as superconducting tunnel junctions (STJs) depends crucially on this quasiparticle lifetime.

Experiment

The measured phase response to an optical pulse can be seen in Fig. 1. The rise stems from the response time of the microwave resonator, which is a function of the loaded quality factor and resonance frequency. The exponential decay can be clearly characterized with a single decay time. Both the intensity and the pulse length are chosen to create a clearly observable response while staying in the linear regime.

The quasiparticle lifetime is known to depend on the choice of material [4]. We have opted for tantalum, because of its demonstrated lifetime and high critical temperature. A 150 nm tantalum layer is sputter deposited onto a HF-cleaned [100] Si wafer. Prior to tantalum deposition a 5 nm niobium seed layer is sputtered to promote growth of the tantalum alpha phase [6].

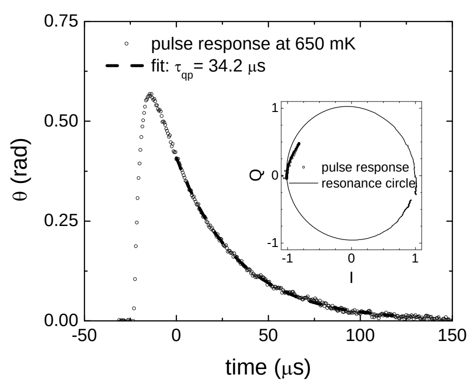

Fig. 1. The phase response to an optical pulse of 0.5 μs, the resonator response time is 3.7 μs. Both timescales are an order of magnitude smaller than the quasiparticle lifetime. The inset shows the response in the IQ plane, the resonator dip is slightly asymmetric.

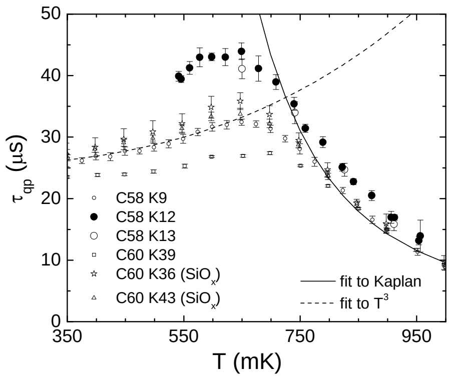

Fig. 2. The temperature dependence of the quasiparticle lifetime for different resonators in the frequency range of 4-6 GHz. With growing temperature, all show an increase in the lifetime until a maximum is reached after which an exponential decay takes over. The error bars are the standard deviation of multiple pulse responses. The lifetime of device K9 is fitted to a cubed temperature dependence and to a theoretical prediction of the recombination time using a gap of 0.27 meV [4].

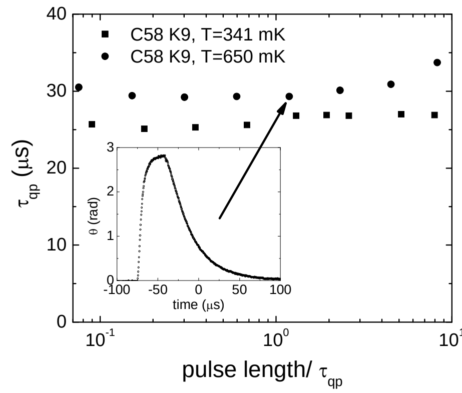

Fig. 3. The quasiparticle lifetime for different pulse lenghts. The excess quasiparticle number at the end of the pulse is related to the pulse length, being around an order smaller or larger than the lifetime. The inset shows the response for a pulse length equal to the lifetime.

Patterning is done using optical lithography and CF_4/O_2 reactive ion etching. The critical temperature is 4.4 K, its residual resistivity ratio is 3. The chip is partly covered with a 10 nm sputtered SiO_x layer.

The devices are quarter wavelength CPW resonators and manifest as a circle in the polar plane of the forward transmission S_{21}. This resonance circle is normalized: it is shifted to the origin and given unity radius, in such a way that at resonance the imaginary part is zero and the real part is minus unity. This scaling allows the response of different KIDs to be compared. Using a signal generator, IQ mixer and 2-channel fast acquisition card the response can be monitored in time, see Fig. 1.

The chip is mounted in a sample box on a He-3 sorption cooler. A GaAsP LED having a rated response time of 10 ns acts as photon source for the optical pulse. The LED is placed at the 4K plate and is optically coupled to the sample box via a plexiglass fiber and illuminates the whole chip.

Due to the broad illumination and small resonator size the resonator and nearby ground plane is rather uniformly illuminated, leading to a homogeneous excitation of Cooper pairs and quasiparticles. This technique allows us to measure the quasiparticle lifetime without being limited by the outdiffusion of quasiparticles.

The quasiparticle lifetime is plotted versus temperature in Fig. 2 for several devices. When cooling down the quasiparticle lifetime increases until it reaches a maximum value at a temperature of 650 mK. Upon further cooling the lifetime starts to drop and seems to reach a saturation value around 350 mK. This feature is followed qualitatively by all devices. Quantitavely the lifetime at high temperatures and the saturation value of different devices lie closely together, however the maximum of the lifetime differs between 27 to 45 μs. Within this spread there is no significant difference in lifetime between resonators covered with a 10 nm SiO_x layer, its presence does not significantly affect the lifetime. The SiO_x layer leads to nearly a doubling of noise in covered resonators. The subject of noise will not be discussed in this article.

We find that the lifetime is independent of pulse duration, see Fig. 3. The lifetime does not change when the sample is shortly heated above the critical temperature. We have not observed a power dependence of the quasiparticle lifetime below the resonator saturation readout power. Near this power the quasiparticle lifetime decreases (not shown).

Discussion

The most striking feature is that the quasiparticle lifetime decreases with decreasing temperature for all devices below 650 mK. This represents a strong deviation from recombination theory for homogeneous superconductors [4], since the quasiparticle recombination time is expected to monotonically increase when cooling down and reaches values in the order of a second around 300 mK for bulk alpha phase tantalum, due to the exponential decrease in quasiparticle density.

The lifetime as depicted in Fig. 2 can be divided in three regimes: the saturation of the lifetime which is visible near 350 mK; the increase of the lifetime up to 650 mK which follows a T^3-dependence; and the subsequent decrease of the lifetime when heating up above 650 mK. The latter can be fitted to the theoretical prediction the recombination time [4], when using a superconducting gap of 0.27 meV, much smaller than that of bulk tantalum which is 0.67 meV.

Upon the absorption of optical photons, the high energy of the quasiparticles generated is quickly downconverted, mostly via electron-phonon scattering. In turn these phonons generate quasiparticles, leading to the photon energy being downconverted to a large number of excess quasiparticles near the superconducting gap [7]. The downconversion is too fast to be observed by the resonator due to the response time.

The quasiparticles recombine and emit phonons. As such, the effective lifetime is governed by the non-equilibrium quasiparticle and phonon densities and corresponding timescales, such as the recombination, Cooper pair breaking and phonon escape rate [5].

However in a superconductor where non-uniformities give rise to subgap states, quasiparticles can become trapped and become localized in a macroscopic depression of the order parameter or a single state. Non-uniformity can arise from vortices, trapped flux, magnetic impurities and metallic oxides. For example, niobium is known to have superconducting oxides with a critical temperature as low as 1.4 K [8], which could explain the choice of gap in the fit to Ref. 4. Detrapping can occur due to phonon absorption or scattering with a quasiparticle [9,10].

The fact that the maximum lifetime differs between devices at the same chip suggests the existence non-uniformity in the superconducting layer. The exact nature and origins of the traps in our devices is unknown. The reproducibility of the result after heating above the critical temperature rules out trapped flux.

We assume that the non-uniformity of the superconducting properties gives rise to an additional quasiparticle loss channel that is much faster.

Qualitatively, the increase in the lifetime with increasing temperature has been observed also in STJs [10]. The responsivity increases with a factor of two due to the lifetime up to around 600 mK, above which it decreases again. These junctions consist of two tantalum electrodes with an Al/AlO_x barrier in between. Quantitatively, the value of the quasiparticle lifetime of up to 45 μs lies in the range of 5-80 μs which has been reported for tantalum in the literature [11-14].

The fact that similar results have been observed in tantalum devices with a dissimilar geometry and material composition suggests that the non-uniformity leading to our observation has a general character.

Conclusion

We have measured the quasiparticle lifetime in tantalum on silicon quarter wave KIDs using optical pulses for temperatures down to 350 mK. We find that the quasiparticle lifetime saturates at low temperatures around 25 μs, grows with increasing temperature and reaches a maximum value of up to 45 μs at a temperature of 650 mK, and drops at higher temperatures. There is no optical pulse length and readout power dependence of the lifetime and there is no significant difference between resonators covered with and without a 10 nm thick SiO_x layer.

We attribute the low temperature behavior of the lifetime to quasiparticle traps arising from non-uniformity in the superconductor. The nature of these traps is unknown and deserves further attention.

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