Sensitivity of a superconducting nanowire detector for single ions at low energy

Michele Sclafani$^1$, Markus Marksteiner$^1$, Fraser McLennan Keir$^1$, Alexander Divochiy$^2$, Alexander Korneev$^2$, Alexander Semenov$^2$, Gregory Gol’tsman$^2$ and Markus Arndt$^1$

$^1$ Vienna Center for Quantum Science and Technology, Faculty of Physics, University of Vienna, Boltzmanngasse 5, A-1090 Vienna, Austria
$^2$ Department of Physics, Moscow State Pedagogical University, M Pirogovskaya Street 1, Moscow 119992, Russia

E-mail: markus.arndt@univie.ac.at

Received 3 December 2011, in final form 16 December 2011
Published 17 January 2012
Online at stacks.iop.org/Nano/23/065501

Abstract

We report on the characterization of a superconducting nanowire detector for ions at low kinetic energies. We measure the absolute single-particle detection efficiency $\eta$ and trace its increase with energy up to $\eta = 100\%$. We discuss the influence of noble gas adsorbates on the cryogenic surface and analyze their relevance for the detection of slow massive particles. We apply a recent model for the hot-spot formation to the incidence of atomic ions at energies between 0.2 and 1 keV. We suggest how the differences observed for photons and atoms or molecules can be related to the surface condition of the detector and we propose that the restoration of proper surface conditions may open a new avenue for SSPD-based optical spectroscopy on molecules and nanoparticles.

(Some figures may appear in colour only in the online journal)

1. Introduction

Over the last few decades, several different classes of cryogenic devices have been proposed for the detection of ionized [1–3] or even neutral [4] particle beams. This comprises cryogenic bolometers [5] and superconducting tunneling junction devices (STJ) [6, 7] as well as normal metal insulator superconductor junctions (NIS) [8].

Here, we focus on one specific variant which relies on the fact that the impact of energetic particles may create localized resistive regions in a superconducting nanowire, which can be visualized as nanosecond voltage pulses when the wire is driven by a constant current source. These detectors were originally designed for telecommunication purposes as single-photon sensors in the infrared radiation band. The literature therefore usually refers to them as superconducting single-photon detectors (SSPD) [9].

Since any device that is highly responsive to small energy changes may also be considered as a detector for massive particles, several research groups have focused on the application of SSPDs in the context of mass spectroscopy [4, 10, 11]. In many experiments clusters or molecules are generated as isolated ionized particles and accelerated to energies in the range of typically 10–30 keV. The time-of-flight in such devices is then characteristic for the particle mass and the only requirement for the final detector is to record the object impact with high efficiency and a time resolution on the nanosecond scale. The general feasibility of this concept has already been demonstrated before and interest has recently been focused on the exploration of detector characteristics such as optimal size, materials, geometry and sensitivity [12, 13].

While the SSPD detection efficiency for electromagnetic radiation was reported to vary between $\eta = 10^{-4}$ and $10^{-1}$ [14], it has often been argued that the impact of massive particles should be detectable with certainty [15] once the kinetic energy suffices to heat the nanowire above the critical temperature. In many practical cases this assumption is easily fulfilled with particle energies exceeding several kiloelectronvolts. In our present contribution we show,
however, that this assumption may fail already for particle energies below a few hundred electronvolts: in many practical cases an atom or molecule arriving at the detector surface will not transfer all of its kinetic energy to the electronic system of the superconducting nanostripe. The incident particle may rather bounce off the surface or convert kinetic energy into cage deformation and internal heat during its impact. Massive particles will also interact with the nanowire phonon system directly in addition to electronic excitations, as usually discussed in SSPD photodetection.

Our present work focuses on the role of surface adsorbates which have remained neglected in all previous studies, so far. They prove to be crucial as they strongly attenuate the energy transfer from the impacting particles to the SSPD Cooper pairs. Liquefied or frozen gases on top of the nanowire are expected to be irrelevant for the detection of photons but they open new dissipation channels for low energy nanoparticles. In the following we will show that the SSPD design can nevertheless be highly sensitive to low energy ions.

2. Experimental set-up

The experimental set-up is schematically illustrated in figure 1: a clean beam of atomic ions is generated by a sputter gun (IQE 11/35), whose extraction energy is varied between 0.2 and 1 keV. The ion current can be controlled via the electron current in the ionizer stage. Our experiments were performed with a number of different noble gases and also SF₆. In the following, we limit our presentation to the case of He⁺, first because the same qualitative behavior was observed for all noble gases and, second, since helium adsorbates are removed more easily from the SSPD surface, if needed. The detector is placed approximately 30 cm downstream of the ion gun and it is mounted on a copper holder in good thermal contact with a liquid helium cryostat. Our nanowire detector consists of a 4 nm thick and 100 nm wide NbN film that was sputtered in a long meander onto a sapphire substrate. The detector covers an area of 20 × 20 μm² with a filling factor of f ≈ 50%. We operate the device in high vacuum (10⁻⁷–10⁻⁹ mbar) and the detector temperature can be varied between T = 3 and 5 K, i.e. well below its critical temperature of Tc = 10 K. In order to prevent thermal fluctuations and to block photons from outside, the detector is shielded by an aluminum cylinder covered with mylar foil.

A wire mesh (G in figure 1) can be optionally inserted in front of the detector entrance window to discriminate between photons and particles. We verified that the detector signal goes back to the background value when the mesh potential equals the ion extraction voltage. This proves that ions were recorded rather than neutral atoms or even photons. The SSPD can be optionally replaced by a Faraday cup (KimballS66) connected to an ammeter whose signal provides a reliable particle number calibration at elevated ion currents.

3. Hot-spot model

Throughout recent years, different models have been suggested to explain the underlying detection process [16–18]. The ‘hot-spot’ model was found to be in good qualitative agreement with experimental observations both for photons and for ions [19, 23]: when a molecule hits the superconducting film an energy transfer occurs and leads to the breaking of a Cooper pair and therefore to the formation of one high energy electron and of an electron whose energy is close to the superconducting gap. The energetic electron transfers its energy to other electrons and phonons and breaks other Cooper pairs. In this avalanche process the concentration of quasi-particles increases on the picosecond timescale and suppresses the superconductivity in a local region, the so-called ‘hot-spot’. The dimension of this hot-spot grows as the quasi-particles diffuse into their surroundings. The supercurrent is expelled from the hot-spot and flows around its outside. As soon as the local current density exceeds its critical value Jc, an ohmic resistance is established over the entire wire cross section. This manifests itself as a measurable voltage peak across the detector. Recently, alternative mechanisms were proposed, assuming the same initial stage of hot-spot formation but attributing the rising resistance to the unbinding of vortex–antivortex pairs [17] as well as vortex penetration into the superconducting film [20]. The probability of vortex formation increases when the superconductivity is suppressed due to ‘hot-spot’ formation. The origin of dark (false) counts in SSPDs was also attributed to vortex and vortex–antivortex formation [21, 22].

An experimental verification of the hot-spot model is usually based on the observation of the detection efficiency η as a function of the detector bias current Ib. Figure 2 traces η for five He⁺ impact energies below 1 keV. We note that we measure the absolute detection efficiency, defined by the ratio of the SSPD ion counts S_{SSPD} and the number of ions seen by the optional calibrating Faraday cup S_{FC} according to η_{abs} = (S_{SSPD} − S_{dark})/(S_{FC}). In this relation we also corrected for dark counts S_{dark} and the meander filling factor f.
the detection efficiency increases with the bias current, in
of the normal-conducting hot-spot. When we fix the energy, $I$, at a
fluctuation-based mechanism, such as vortex formation. At
the 'hot-spot' exceeds the critical current density, at low bias
is formed when the current density in the 'sidewalks' around
resistance barrier is created. While at high bias the resistive barrier
This 'kink current' may be attributed to a change in the
response mechanism: while at high bias the resistive barrier
the hypothesis that more sensitive electronics will also allow
us to see even slower particles. In the present experiments the
minimum test energy was determined by the ion source. At
high energies and at high bias currents the detector saturates
with an absolute detection efficiency of 100%, as expected.

A number of observations can be made in comparison
to earlier work [23]: first, we confirm the hypothesis that
narrower nanowires are more energy-sensitive than wider
structures. While the former experiments detected no signal
for ion energies lower than $E_{kin} = 600$ eV in a detector with
$w = 800$ nm wide stripes, we still see a measurable signal at
200 eV for wires with $w = 100$ nm. In contrast to the earlier
work, we find no threshold behavior either. This gives rise to
the hypothesis that more sensitive electronics will also allow
us to see even slower particles. In the present experiments the
minimum test energy was determined by the ion source. At
high energies and at high bias currents the detector saturates
with an absolute detection efficiency of 100%, as expected.

Qualitatively one may identify two regions of approxi-
mately exponential increase in $\eta(I_b)$, approximated by straight
lines in the logarithmic plot, which are joined around a
'kink bias current' $I_{kb}$, as shown in the inset of figure 2. This 'kink current' may be attributed to a change in the
response mechanism: while at high bias the resistive barrier
is formed when the current density in the 'sidewalks' around
the 'hot-spot' exceeds the critical current density, at low bias
the formation of the resistive barrier can be related to a
fluctuation-based mechanism, such as vortex formation. At
fixed $I_b/I_c$, the increase of $\eta$ with $E_{kin}$ is attributed to a growth of
the normal-conducting hot-spot. When we fix the energy,
the detection efficiency increases with the bias current, in
agreement with figure 2.

In contrast to the procedure chosen by Suzuki et al [23], we
follow Verevkin et al [19] and derive an estimate for the
hot-spot radius $R$ from the ratio between the kink bias current
$I_{kb}$ and the critical current $I_c$:

$$R = \frac{w}{2}\left(1 - \frac{I_{kb}}{I_c}\right).$$  (1)

From curves as shown in the inset of figure 2 we estimate
the hot-spot radius $R_{ion}$ for different ion energies and find it
to vary between $R_{ion} = 18$ nm at 200 eV and $R_{ion} = 22$ nm at
1 keV.

Based on a linear extrapolation to the model of Verevkin
et al [19], we can compare these radii to those expected for
photons at the same energy $R_p(E) = R_{ion}$, which would
amount to $R_p(0.2$ keV) = 210 nm and $R_p(1$ keV) = 470 nm,
respectively. To quantify this difference between impacting
matter and photons we introduce the conversion equivalent:

$$\rho_c = \frac{R_{ion}(E)}{R_p(E)},$$  (2)

which ranges between $\rho_c = 5–10\%$ in our case.

We may use the estimated hot-spot area to define a
detection-equivalent photon energy $E_d$, i.e. the energy a
photon would need to create a hot-spot as large as observed
for the ions. We find $E_d = 1.8$ eV for $E_{ion} = 200$ eV and $E_d = 2.6$ eV for $E_{ion} = 1$ keV. We interpret this as an indication that
by far the largest fraction (>99%) of the incident ion energy is
not transferred to the electronic system of the superconductor
at all.

4. Role of the surface adsorbates

Many reasons may be invoked for the incomplete transfer of
kinetic energy: while photons couple directly to the electronic
system and only as a consequence of that to phonons as well,
the incident ions are expected to interact with both systems
at once. In the case of complex molecules, the impact may
also redistribute energy between the translational and the
internal degrees of freedom via inelastic deformations. One
more dissipation channel is related to surface adsorbates that
accumulate on the cold detector surface and act as a damping
cushion, even at a base pressure of $10^{-8}$ mbar.

In order to demonstrate the relevance of surface
adsorbates we recorded the relative detection efficiency while
varying the surface conditions of our detector by allowing
helium to gradually condense on it: with the ion gun switched
off, we raised the residual helium pressure in the chamber to
10\(^{-5}\) mbar for about 60 s. A few seconds later the pressure
was restored to $10^{-7}$ mbar and the ion gun was turned on
again.

Figure 3 shows the detection efficiency as a function of the
integrated adsorbate accumulation time for He\(^+\) ions at an
energy of 300 eV. In this setting, we find an exponential decay of $\eta$. With increasing surface coverage the efficiency drops
by as much as a factor of 1000. The causal relation between
the decreasing detection efficiency and surface condensates is
corroborated by the observation that we can largely restore the
efficiency by locally heating the chip. Since the ohmic
resistance of the nanowire is too small to dissipate enough
power and to effectively heat the chip, we mounted a black
absorber on the backside of the SSPD sapphire substrate and
used a blue laser (447 nm, 1000 mW) for up to 5 min to
partially evaporate the surface contaminations. This allowed
us to regain a factor of 100 in detection efficiency.

5. Prospective sensor applications

In our discussions so far, we have focused on the detection
efficiency as a function of the SSPD bias current (figure 2) or
surface adsorbates (figure 3). A quantitative characterization of $\eta$ is sufficient to understand and devise the SSPD as a detector for mass spectrometry.

In the following we go one step further and propose a specific application in optical spectroscopy on molecules and nanoparticles. In order to elucidate this field, we refer to figure 4 where we plot $\eta$ as a function of the impact energy for $I_b/I_c = 0.25$. The interesting information is revealed in the inset when we find that an energy variation by as little as 5 eV may already lead to an increase in the detection efficiency of 50%.

We note that in this particular experimental realization the detection efficiency is smaller than the one shown in figure 2. At least two effects contribute to this observation: first, the surface coverage was not controlled in this experiment, as we were interested in relative efficiencies, only. Second, the critical current of each chip decreases with its extended exposure to energetic ions. The creation of a single local defect in the nanowire suffices to affect the detection efficiency. For the data shown in figure 4 the critical current $I_c = 10 \mu A$ was half the value typically observed for new chips. Although the sensitivity to surface contaminations and other detector specificities would render an absolute energy measurement difficult, small energy differences may still be detected rather reliably.

We here suggest that it will be feasible to measure small variations in atomic or molecular energies. If SSPDs can be made sensitive to the internal energy of nanoparticles—which remains to be explored in future experiments—the required energy modulation could be imparted in a typical photon absorption spectroscopy experiment where the probability of the energy transfer is modulated by scanning the frequency of the incident light. Many large molecules and nanoparticles convert this excitation energy into vibrations and store it up for their impact on the detector.

One may also convert internal to kinetic energy before the impact: helium nanodroplets composed of $10^4$–$10^8$ atoms [24, 25] may act as 380 mK coolants for organic molecules and provide an ideal environment for spectroscopy. We here propose a new kind of depletion spectroscopy, where the absorbed photon triggers the evaporation of several thousand helium atoms. If the evaporation is isotropic the net velocity remains unchanged, while both mass and kinetic energy are reduced by several per cent. This setting should open a new window for single-photon absorption spectroscopy.

6. Conclusion

Our experiments show that superconducting nanowires are capable of recording atomic and molecular ion signals at energies much lower than typically used in mass spectrometry. We have determined the absolute single-particle detection efficiency and find that it is feasible to achieve a detection efficiency of 100%, in our setting for ion energies below 1000 eV. This saturation energy is still orders of magnitude larger than expected under the assumption that the ions couple predominantly to the electronic system of the superconductor.

We have identified several possible dissipation channels and discuss here for the first time the relevance of surface adsorbates. Because of their transparency to visible and IR light, they went unnoticed in all earlier photon counting experiments. They might, however, also compromise optical detection experiments in the vacuum-ultraviolet wavelength range, if the surface adsorbates contain a large fraction of oxygen (residual air). For molecules even a thin damping layer can reduce the detection efficiency by several orders of magnitude. This observation is important for defining strategies, such as intermittent detector heating, to maintain proper surface conditions over extended periods of time.

The observed sensitivity of the SSPD to the particle energy may open a new avenue for optical spectroscopy on molecules, nanoparticles and even doped helium nanodroplets which will be interesting for further studies in the future.

Acknowledgments

We acknowledge financial support through the Austrian FWF grant (Z149-N16, Wittgenstein) and MS acknowledges fruitful discussions with M Ohkubo.
References

[1] Twerenbold D, Vuilleumier J L, Gerber D, Tadsen A, van den Brandt B and Gillevet P M 1996 Appl. Phys. Lett. 68 3503–5
[2] Frank M, Labov S E, Westmacott G and Benner W H 1999 Mass Spectrom. Rev. 18 155–86
[3] Suzuki K, Ohkubo M, Ukibe M, Shiki S, Miki S and Wang Z 2010 Rapid Commun. Mass Spectrom. 24 3290–6
[4] Marksteiner M, Divochiy A, Sclafani M, Haslinger P, Ulbricht H, Korneev A, Semenov A, Gol’tsman G and Arndt M 2009 Nanotechnology 20 45501
[5] Cavallini M, Gallinaro G and Scoles G 1967 Z. Naturforsch A 22 413–4
[6] Shiki S, Ukibe M, Ohkubo M, Hayakawa S, Sato Y and Tomita S 2009 Physica C 469 1674–6
[7] Ohkubo M, Shiki S, Ukibe M, Tomita S and Hayakawa S 2011 Int. J. Mass Spectrom. 299 94–101
[8] Hilton G C, Martinis J M, Wollman D A, Irwin K D, Dulcie L L, Gerber D, Gillevet P M and Twrenbold D 1998 Nature 391 672–5
[9] Goltsman G N, Okunev O, Chulkova G, Lipatov A, Semenov A, Smirnov K, Voronov B, Drzandan A, Williams C and Sobolewski R 2001 Appl. Phys. Lett. 79 705–7
[10] Suzuki K, Miki S, Shiki S, Wang Z and Ohkubo M 2008 Appl. Phys. Express 1 031702
[11] Casaburi A, Zen N, Suzuki K, Ejrnaes M, Pagano S, Cristiano R and Ohkubo M 2009 Appl. Phys. Lett. 94 212502
[12] Zen N, Casaburi A, Shiki S, Suzuki K, Ejrnaes M, Cristiano R and Ohkubo M 2009 Appl. Phys. Lett. 95 172508
[13] Casaburi A, Ejrnaes M, Zen N, Ohkubo M, Pagano S and Cristiano R 2011 Appl. Phys. Lett. 98 023702
[14] Goltsman G et al 2009 IEEE Trans. Appl. Supercond. 17 246–51
[15] Ohkubo M 2008 Physica C 468 1987–91
[16] Semenov A, Goltsman G and Korneev A 2005 Physica C 352 349–56
[17] Semenov A, Engel A, Hübbers H W, Il’in K and Siegel M 2001 Eur. Phys. J. B 47 495–501
[18] Maingault L, Tarkhov M, Florea I, Semenov A, Espiau de Lamaestre R, Cavalier P, Goltsman G, Poizat J P and Villegier J C 2010 J. Appl. Phys. 107 116103
[19] Verevkin A, Zhang J, Sobolewski R, Lipatov A, Okunev O, Chulkova G, Korneev A, Smirnov K, Goltsman G N and Semenov A 2002 Appl. Phys. Lett. 80 4687–9
[20] Bulaevskii L N, Graf M J and Kogan V G 2011 arXiv:1108.4004
[21] Bulaevskii L N, Graf M J, Batista C D and Kogan V G 2011 Phys. Rev. B 83 144526
[22] Berdiyorov G R, Milošević M V and Peeters F M 2009 Phys. Rev. B 79 184506
[23] Suzuki K, Shiki S, Ukibe M, Koike M, Miki S, Wang Z and Ohkubo M 2011 Appl. Phys. Express 4 083101
[24] Toennies J P and Vilesov A F 2004 Angew. Chem. 43 2622–48
[25] Pentlehner D, Riechers R, Dick B, Slenczka A, Even U, Lavie N and Brown Rand Luria K 2009 Rev. Sci. Instrum. 80 043302