Superconducting Molecule Detector

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ABSTRACT

We present the realization of a universal superconducting nanowire detector (SNWD) which may serve the detection of particles as diverse as photons, or atomic and molecular ions. The detector is triggered by the surface deposition of energy that breaks superconductivity in a thin nanowire at constant bias current. It combines speed with ruggedness, high spatial resolution and high saturation threshold. While a single pixel detector was foreseen in SUMO, here we have already realized and characterized an 8-pixel detector in a cryogenic ultrahigh vacuum chamber. Large area SNWD detectors are expected to become important for mass spectrometry, beam profiling in high-energy and nuclear physics, for fundamental tests of quantum physics, dark matter searches, and single molecule analysis.

Keywords: Superconducting nanowire detector, Quantum detector, Atomic and Molecular beams, Mass spectrometry

1. INTRODUCTION

In recent years, quantum detection has attracted an increasing interest since the exploitation of quantum principles can boost the response of detectors to particles, or fields often by orders of magnitude over existing devices in sensitivity, speed or resolution. The project SUMO has focused on exploring superconducting nanowire technology for the detection of massive particles in atomic and molecular beams with future promise in particular in beam profiling and mass spectrometry [8] as well as quantum-enhanced molecular analysis. Superconducting nanowire detectors (SNWDs) feature energy sensitivity at low energies and become straight event detectors at high energy. They may be built to have 50 nm spatial resolution or less and they can respond within picoseconds to photons or matter. They are expected to be sensitive to particles such as electrons, atoms and molecules but even beams of biological nanomatter or aerosols, if the energy transfer to the detector surface can be ensured. They are expected to break new grounds in mass spectrometry, molecular beam detection as well as in molecule metrology.

Throughout the last twenty years, superconducting nanowire systems have emerged as ultrafast and ultrasensitive photon detectors [7], with applications from quantum information [2] over laser ranging [5] to infrared astronomy [10]. It has been demonstrated that a single visible or even near-infrared photon can break the superconductivity in a 100 nm wide nanowire and trigger a voltage pulse if the system is driven by a constant bias current.
The aim of SUMO was to prove the principle viability of the idea in a clean setup. We have fabricated an 8-pixel array of NbTiN nanowire detectors, each 20×20μm^2 large. We have tested and characterized them for visible light and then embedded them into a cryogenic system in ultra-high vacuum to test the detector byte with atomic ions of different mass, energy and flux. We show how to distinguish photons and ions by the detector bias current that is required to retrieve a signal and by the signal response to external magnetic fields. We can saturate the detector at low particle energies and interpret this as an indication for the complete detection of all ions within the detector surface area. We discuss the conditions to maintain the detector stable and the influence of its vacuum environment. Our results feed into an ongoing EU FET Open project (SuperMaMa) and pave the path to an extended follow-up project in ATTRACT Phase 2.

2. STATE OF THE ART

In SNWDs a superconducting film of typically less than 10 nm thickness is fabricated into a meandering wire of about 100 nm width. Small energy impacts can already break the superconductivity and a picosecond fast quantum-phase transition results in a clearly visible voltage pulse if the wire is driven by a constant bias current of the order of 10-20 µA.

The vast majority of earlier studies in the field have focused on applications in photonics and have already resulted in successful commercial products for photon correlation, quantum communication, or laser ranging.

A small number of pioneering experiments have recently started exploring the application of SNWDs for molecular ions [9] and even neutral molecules [4, [6], aiming at improved detectors for mass spectrometry and molecule analysis.

Mass spectrometry has become a ubiquitous technology in physics and chemistry, in pharmacy and medicine, in monitoring of transport and nutrition safety. It serves in the detection and analysis of environmental pollutants, of drugs, proteins, or genes and it is expected to reach an annual market value of 10 billion Euros in the next few years.

Many mass spectrometer systems such as magnetic sector field analysers and quadrupole mass spectrometers are optimized for molecular systems with a mass-to-charge ratio up to 4000 amu/e, while time-of-flight mass spectrometers would usually be operated at m/q < 10^5 amu/e. One reason for such upper bounds is the need to sort the ions in electro-magnetic fields. This requires time and therefore low kinetic energy. However, this contradicts the demands of most of the common ion detectors: secondary electron multipliers and microchannel plates. They require particle velocities of typically $v > 10^4$ m/s and acceleration voltages way beyond 20 kV, if efficient ion detection shall still be ensured for high-mass proteins or aerosols [1].

In addition to mass spectrometry, which yields information about molecular composition, the deflection of molecular beams can retrieve electronic, magnetic, optical and structural information about the particles of interest. Such experiments require the highest possible spatial resolution. Secondary electron multipliers may have pore sizes down to 5 µm and yet be practically limited to several 10 µm by electron scattering.

3. BREAKTHROUGH CHARACTER OF THE PROJECT

Superconducting nanowires are promising for particle detection because they combine many useful parameters in a single robust device. We compare their features and challenges with those of secondary electron multipliers (SEMs) in Table 1:

While sector field and quadrupole mass spectrometers are insensitive to detector response time, time-of-flight spectrometers require detection time bins of about 1 ns for mass resolution of the order of $\Delta m : m \simeq$1:10’000 and even slower response is tolerable for high mass ions as in the same acceleration potential. Nanosecond time scales can be readily achieved with SEMs, but the demonstrated potential of small SNWDs pixels is as short as 7.7 ps [2]. The maximal count rate in ion detectors depends on the device type. Channel electron multipliers and photo cathodes are often restricted to 10 MHz count rates in order not to destroy the photo-anode after intrinsic electron amplification by a factor $10^5 - 10^7$. Lacking any thermal effects up to the detection threshold, SNWDs are thermally well protected and can, in principle, reach up to 10-100 times higher maximal count rates. This promises higher dynamic range in later commercial applications.

The spatial resolution of SEMs can be easily beaten by SNWDs. Already the simple prototype demonstrated here, with 20 µm width, resolves position as well as some of the best available SEMs. The ultimate resolution limit is only given by the SNWD line widths and may eventually even reach down to below 100 nm, two orders of magnitude better than any SEM. This will become important in deflectometry experiments.

SEMs are sensitive to the ion energy but require a minimal ion velocity of >10^4 m/s. For high mass ions this corresponds to acceleration voltages of > 20 kV. The sensitivity of SNWDs to particle energy is still an open field of research, as it depends on various parameters: Intrinsically it should be sensitive down to 1-10 eV, energies recorded when a single photon is absorbed. However, much experimental work and theoretical modelling is still required to understand how kinetic or internal particle energy couple to the superconducting system. The coupling may be strongly modified by layers of adsorbents and cushioning effects, which we observe at high gas loads of condensable noble gas ions.

While detector size is still a clear argument in favour of SEMs, we foresee that changes in material and geometry in combination with multipixel architectures will enable photolithographic manufacturing of nanosecond fast SNWDs with a large detector area.

The comparison explains the present-day reasons for the commercial use of electron multipliers, but we also recognize the potential for orders of magnitude improvement in resolution, response time and energy sensitivity and detector area for SNWDs.

Parameter	SEMs	SNWDs
Response time	> 100 ps	> 20 ps
Max count rate	<10 MHz	< 100 MHz
Resolution limit	< 10 µm	< 100 nm
Sensitivity to **internal** energy	> 10-15 eV (metastable atoms)	< 1 eV (expected)
Sensitivity to **kinetic** energy	velocity dependent	> 1-3 eV (expected)
Threshold velocity	> 10’000 m/s (ions)	energy dependent
Detector size	Square inch, Megapixel	Potential for > square inch

Tab. 1. *Comparison of key parameters of secondary electron multipliers (SEMs) and superconducting nanowire detectors (SNWDs). The table lists the extremes, which cannot necessarily all be realized in the same detector configuration. There is always a necessary trade-off between speed and size and cooling requirements*

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4. PROJECT RESULTS

4.1. Fabrication of an 8-pixel SNWD Byte

The fabrication principle is similar to that for superconducting single photon detectors (SSPD). A NbTiN film with a thickness of about 10 nm is deposited onto an oxidised silicon waver. Electron lithography is used to write eight meanders, each with 20×20 µm² surface area and a filling factor of 50%. The pixels are placed on a printed circuit board surrounded by Faraday surfaces for ion current measurements. All cables are thermally grounded, and the chips are cooled to 3.9 K by a pulse tube cooler (Sumitomo). While superconductivity holds up even to beyond 10 K, temperatures below 4 K are found to be important and sufficient to avoid non-linear thermal response and to achieve stable low-noise operation.

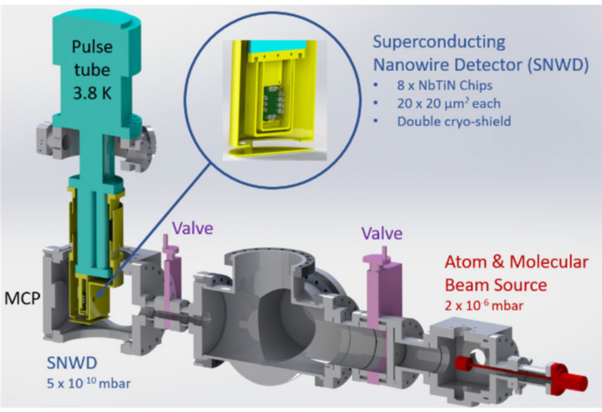

Fig. 1: Molecular beam and SNWD *detector setup. Noble gas ions between 0.1 and 5 keV were generated in a sputter gun. Fast neutral atoms and molecules can be ejected by an Even Lavie valve [3].*

4.2. SNWD characterization

Figure 1 shows the setup at the University of Vienna, comprising the beam source on the right and terminating in the *Single Quantum* SNWD detector byte on the left. A noble gas ion beam, either He^+, Ne^+, Ar^+, Kr^+, Xe^+, can be emitted by an ion sputter gun (Specs) and is directed at the differentially pumped SNWD chip. The detector byte is situated inside a cryogenic shield at 3.9 K, 1 m further downstream in a differentially pumped UHV environment at 5×10^{-10} mbar. At low detector bias current – $I_{bias} =$ 6-10 µA are adapted to the needs of 100-1000 eV ions – we find dark count rates below $C_{dark} < 0.5$ Hz. The pixels show superconductivity, that is a voltage drop of U=0 V across the wire, up to $I_{bias} =$ 20-24 µA.

The sensitivity to source and black body photons increases exponentially beyond $I_{bias} =$ 12-16 µA and saturates about 10^7 Hz. This seems to suggest the need for severe optical shielding to avoid overshadowing of the much rarer atomic or molecular events. However, by design and nature of the nanowire the photon signal is exponentially suppressed by orders of magnitude at a *low* bias current, that is still fully compatible with maximal detection sensitivity for massive particles at kinetic energies $E_{kin} > 10 - 100$ eV. This is seen in Figure 2:

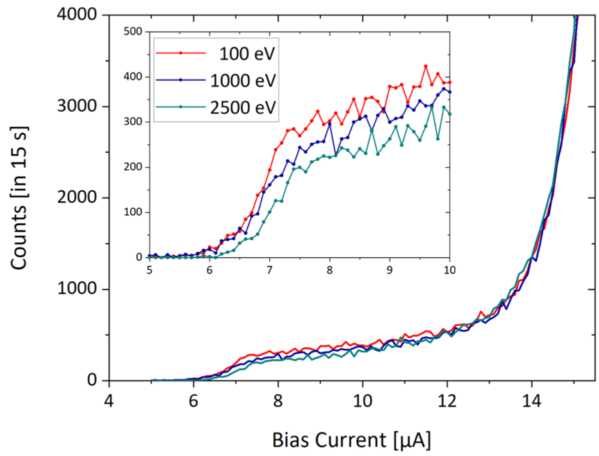

***Fig. 2: Discriminating ions and photons** by their bias current threshold. The onset of counts at $I_{bias} = 6$ µA is due to ions. Photons start at about 10 µA.*

We plot the number of detected He^+ ions with a kinetic energy from 0.1 - 5 keV and at constant ion emission current as a function of the detector bias current. The ion count rate saturates at $I_{bias} = 9 - 10$ µA and at 500 cps, corresponding to an ion flux of 8×10^6 s^{-1}cm^{-2}. The ion plateau is clearly separated from the detection threshold for visible photons, by a safe margin of almost 4 µA.
The count rate is found to be independent of ion kinetic energy since a few eVs of energy already suffice to trigger the quantum phase transition.

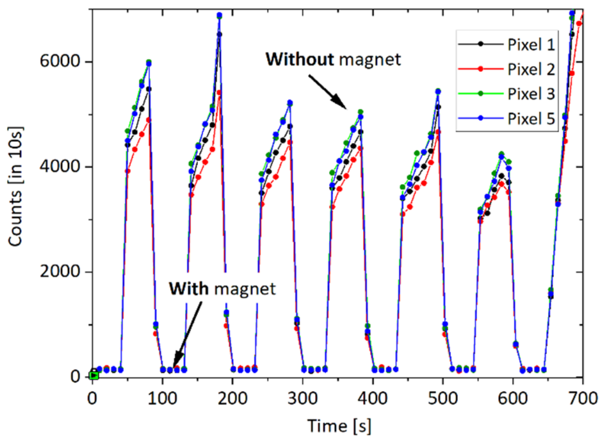

***Fig. 3: Discrimination of ions from neutral atoms** by magnetic fields. He^+ ions flying with 1keV energy are deflected by a localized B-field and miss the detector.*

To verify that we detect single ions rather than much more abundant and multiple neutral atoms, a permanent

magnet ($H > 0.5$ T) was added to the outside of the CF 63 DN vacuum tube. The reduction in count rate by ion deflection due to the Lorentz force is seen in Figure 3.
Varying the ion current in the source changes the flux arriving at the SNWD. This relation is expected and found to be linear within the experimental uncertainties, as shown in Figure 4.

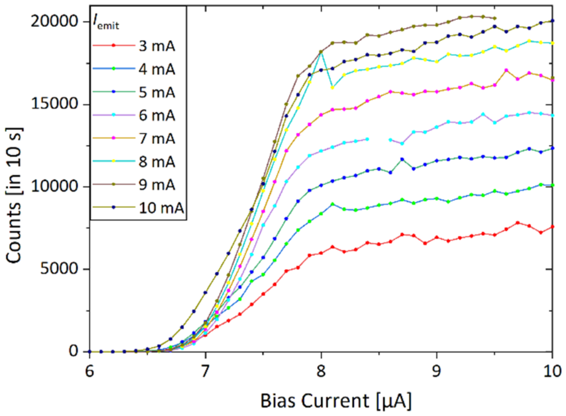

Fig. 4: Linearity of the detection process. Influence of the ion source emission current on the SWND counts in pixel 5. E_{ion} (He^+) = 1 keV. T_{SWND} = 3.9 K.

5. FUTURE PROJECT VISION

5.1. Technology Scaling

Expanding on the ideas of SUMO, an EU FET Open project has already been granted. This shows the general interest in quantum technology and molecular technology. In this FET Open project, called *Superconducting Mass Spectrometry and Molecule Analysis* (EU SuperMaMa), we are developing novel tools to optically prepare neutral and charge controlled biopolymer beams, to develop new mass analysers and to create a **128 bit nanowire array** as well as the required cryogenic electronics, aiming at bringing our technology to TRL 5. UNIVIE and SQ have teamed up with Jan Commandeur/MSVISION as an expert SME in mass spectrometer developments, Edoardo Charbon/ EPFL Lausanne for cryogenic electronics development and Marcel Mayor/University of Basel for developing new chemical techniques to prepare high-mass/low-charge biopolymer beams.
Complementary to that, **ATTRACT *phase 2*** is needed as an essential funding source to upscale this detector technology and to pursue complementary pathways towards increasing the detection area to $\boldsymbol{A_{\text{det}} > 1\ \text{cm}^2}$. This goal will be achieved by increasing the pixel size as well as their number. Since our consortium comprises strong industrial partners in mass spectrometer and detector design, we will be able to step up by two TRL levels to allow demonstration installations at potential customers sites. We see a wide application area for customers working in the fields of mass spectrometry, aerosol science, astronomy, infrared spectroscopy, chemistry, biology and material science.

5.2. Project Synergies and Outreach

We will seek synergies with other ATTRACT projects, in particular on superconducting detector development, aerosol, clean air monitoring and spectroscopy. We have been in contact with a few of them especially in the field of imaging and electronics. In ATTRACT Phase 2 we would facilitate the visibility of the consortium through different channels, following the model of EU SuperMaMa, such as scientific publications, patent strategies, a website and a twitter account.

5.3. Technology application & demonstration

Sensitive, large scale, spatially resolving particle detectors will become important in numerous scientific and technology applications. If SNWDs can be realized with a large detector area and still sub-nanosecond time resolution, the potentially much higher position resolution and much better energy resolution could outperform the very wide-spread secondary electron multipliers (SEM) and additionally open new fields in spectroscopy which are beyond any SEM application. Further projects will involve even more university partners with wider interest in mass and optical spectrometry. We can build on the available expertise and excellent research infrastructure available for this project.

5.4. Technology commercialization

Single Quantum has an outstanding track record in manufacturing and commercializing superconducting detector technology for photonics, with more than 100 superconducting systems installed around the world.
Single Quantum has teamed up with MS VISION in EU SuperMaMa, as an SME in mass spectrometry and a potential OEM integrator for SNWD technology. This combination ensures that new developments in ATTRACT Phase 2 will have good chance for commercialization. Once we have developed a Minimum Viable Product, we will use the established sales and customer channels. If it is needed to up-scale production, it is conceivable to find private investors in the emerging fields of quantum, security and health technologies.

Envisioned risks

Many individual elements have already been proven. The technology challenge is great but foreseeable: A key to stepping up in size and pixel number is a change in fabrication technique (from electron writing to photolithography), which requires further material and ion tests. The thermal management will be a big issue which can be tackled by intense research in cryogenic electronics and refined (event-triggered) readout strategies, as well as by material changes to higher T_c. There are interesting applications for a variety of different outcomes: even if large chips are harder to make, finer resolved detectors will find interesting applications.

5.5. Liaison with Student Teams & Socio-Economic Study

Our SUMO team is home to one master student and three bachelor students/interns, who contributed to the project on all levels: in the ion simulations, CAD design and physical setup of the cryo-detectors and molecular beam machines as well as the acquisition and processing of the final measurements. In ATTRACT Phase 2, students will be involved in the design of superconducting elements, in laser physics and mass spectrometry. They will get to advanced laboratory techniques in fast data acquisition, processing, electronics, molecular design and physical chemistry. These young researchers are intrigued by the potential of quantum detectors in applications ranging from particle analysis to the foundations of science. The integration and training of the next generation has proven essential to the SUMO team, and it has inspired our next steps in research. In ATTRACT Phase 2, the local team leaders are again responsible for the guidance and mentoring of these young researchers, coordinated by the node leader of UNIVIE.

The SUMO 2 consortium will contribute to the *socio-economic study* of ATTRACT phase 2 with data from our industry partners in mass spectrometry, experts in cryogenic electronics, the partners in superconducting detection as well as from physical chemistry to elucidate the role of efficient detectors for neutral particle beams in biomolecular research, mass spectrometry, safety & health monitoring and microscopy.

6. ACKNOWLEDGEMENT

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