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Infrared superconducting single-photon detectors

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14. ABSTRACT

This report culminates a contract tasking Heriot-Watt University to explore design and fabrication of superconducting nanowire single-photon detectors (SNSPDs). Using Heriot-Watt's electron beam lithography system, Dr. Hadfield's group realized small microstrip devices, the next iteration of which may narrow the line width to below 100 nm, entering the single-photon detection regime in the infrared region. Exploring the design of single-photon "camera" devices, the group manufactured a prototype SNSPD device with a single wire of varying thickness; by exploiting timing measurements, they were able to determine if light was focused on one end of the camera device or the other, helping localize the impact of photons. To maximize the probability of mid-infrared photon absorption triggering a SNSPD, Dr. Hadfield's group employed EOARD funding to explore low energy gap superconducting materials which require sub Kelvin operating temperatures, which should enable operation of fibre-coupled and microscope-coupled superconducting devices (at the time of the final report, the cryostat is not yet complete; completion estimated in early 2013). During the investigative period the PI publish 7 original papers in refereed journals and completed the first major review on this field and delivered several webcasts on infrared counting technologies, and EOARD funding enabled three conference presentations. PI has accepted the position of Professor of Photonics at University of Glasgow, UK, and his future work will occur there, with a nanofabrication facility and will explore superconducting detectors with integrated waveguide circuits and novel deposition techniques.

15. SUBJECT TERMS

EOARD, Quantum Information Processing, Single Photon Detector

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EOARD/AFOSR Final Report

Infrared Superconducting Single-Photon Detectors

Dr Robert Hadfield, Heriot-Watt University, UK, 5th October 2012

SUMMARY

This report describes research work carried out at Heriot-Watt University, Edinburgh, UK enabled by support from the EOARD from September 2011 – October 2012. This research was concerns a new type of infrared single-photon detector, the superconducting nanowire single-photon detector, which offers low noise, high timing resolution, infrared single photon sensitivity, and holds promise for a wide range of applications, from optical quantum information science to new methods of medical imaging. Specific accomplishments include (1) development of fabrication capability for superconducting nanowires, (2) exploration of a novel device concept for an infrared photon counting camera and (3) low (sub Kelvin) testing capability for nanowires based on amorphous superconducting materials. An outlook on future research avenues is also given.

1. BACKGROUND

1.1 Research Field: Superconducting nanowire single photon detectors

Infrared single photon detection in a superconducting nanowire was demonstrated a decade ago [1]. The basic superconducting nanowire single photon detector (SNSPD) device is a narrow (100 nm) wire fabricated from an ultrathin superconducting film (typically niobium nitride, NbN). The wire is cooled below the superconducting transition temperature and biased just below the critical current (the point where it will switch into the resistive state). A photon impinging on the wire will create a resistive hotspot, perturbing the current distribution and triggering an output voltage pulse. Since the initial demonstration, device designs have evolved rapidly [2], leading to increased active areas suitable for coupling with optical fibre [3] , enhanced efficiency through the use of optical cavities [4,5], and demonstration of multipixel nanowire devices. SNSPDs offer superior signal-to-noise to conventional off-the-shelf infrared photon counters such as InGaAs single photon avalanche diodes [6,7]. SNSPDs have been implemented into practical detector systems [8], and have been employed in groundbreaking experiments in optical quantum information science, including world record quantum cryptography demonstrations [9] and operation of quantum waveguide circuits at telecom wavelengths [10]. Beyond the quantum arena, SNSPDs are also under consideration for applications such as integrated circuit testing [11], time of flight ranging [12] and fibre temperature sensing [13]. A new generation of SNSPDs are eagerly awaited: increased detection areas and high practical efficiency in the mid-infrared are particularly sought after attributes.

1.2 Research Environment at Heriot-Watt University

The PI, Dr Robert Hadfield, arrived at Heriot-Watt University in 2007 having spent a highly successful postdoctoral period at the US National Institute of Standard of Technology in Boulder, Colorado. He has rapidly built up a suite of facilities for low temperature infrared testing SNSPDs. Specialist capabilities include a low temperature miniature confocal microscope with piezoelectric nanopositioners enabling mapping of device properties with sub-micrometre precision [14]. In 2009, under the Scottish Universities Physics Alliance SUPA II funding initiative Heriot-Watt University acquired a Raith Pioneer electron beam lithography system. This system was commissioned and co-managed by the PI. This high performance nanofabrication instrument will enable in-house fabrication of superconducting nanowire single photon detectors for the first time.

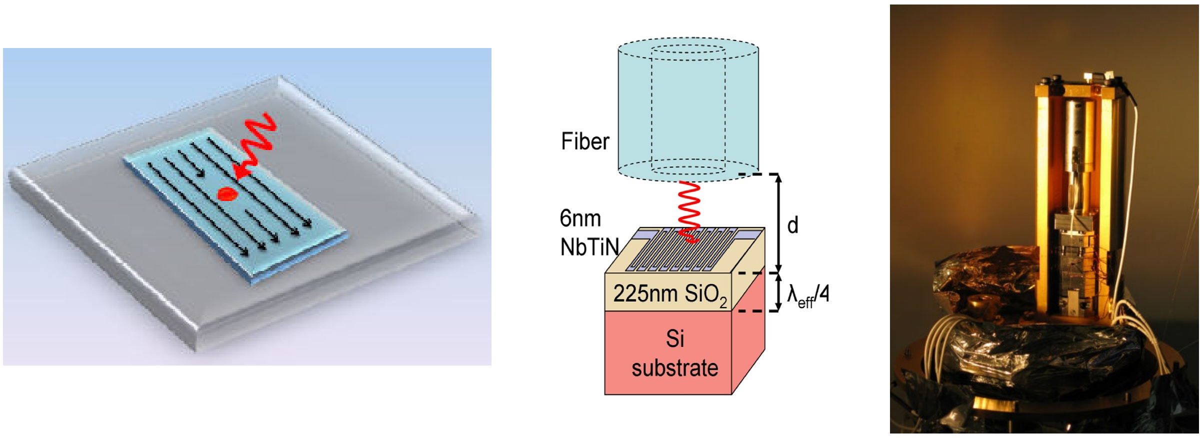


Figure 1 (*left to right): superconducting nanowire single photon detector (SNSPD) device concept. Large area cavity enhanced SNSPD suitable for fibre coupling [5]. Nano-optical testing capability at Heriot-Watt University.*

2. KEY ACCOMPLISHMENTS

2.1 Fabrication of superconducting nanowires at Heriot-Watt University

The EOARD funding award was a major boost to superconducting device fabrication efforts at Heriot-Watt University. Although equipment has been in place since 2010, manpower to initiate device fabrication and process optimisation has been absent. The PI seized the opportunity to employ Dr Alessandro Casaburi (formerly of CNR-Naples, Italy and AIST, Tskuba, Japan) to accelerate device fabrication efforts at Heriot-Watt. Dr Casaburi has over 8 years of superconducting nanowire device fabrication and testing experience. Dr Casaburi joined the group in May 2012, and has rapidly moved forward in initiating device patterning and testing. Examples of his work are shown in Figure 2. The microstrip devices tested so far give promising current voltage characteristics and respond to bright optical pulses. In the next fabrication iteration (scheduled for mid October 2012) Dr Casaburi

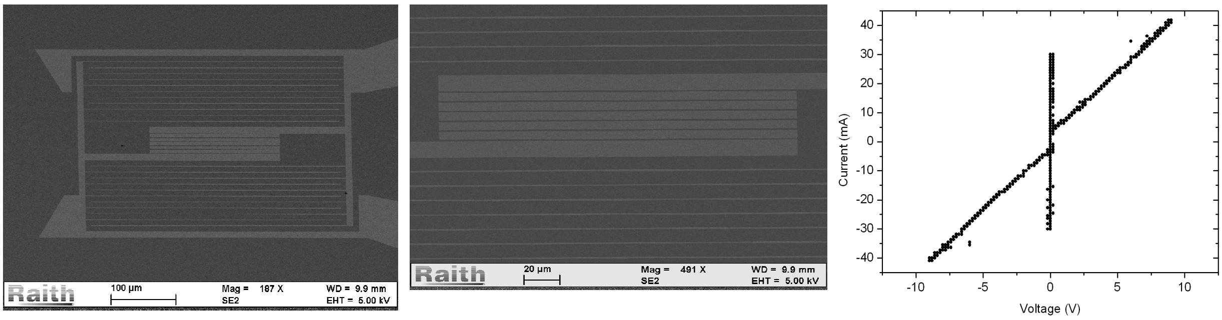


Figure 2*: Superconducting test devices fabricated at Heriot-Watt University by Dr Alessandro Casaburi, summer 2012. Left: Scanning electron micrograph images of microscopic wires; Right: Current-voltage characteristic measured at 4 K showing superconducting behaviour.*

will narrow the linewidth to below 100 nm. This should enable us to enter the single photon detection regime in the infrared (photon energies below 1 eV).

2.2 Towards an infrared photon counting camera

Recent studies by the PI and his group have given new insights into the device physics of SNSPDs [14]. Using nano-optical testing techniques the team have performed local mapping (with microscopic precision and tens of picoseconds timing resolution) of the performance characteristics (efficiency, timing jitter, output pulse delay) of SNSPD devices. These measurements showed that non uniformity in the nanowire leads to varying hotspot resistance, leading to measureable variations in output pulse timing (on tens of picoseconds timescales). This discovery inspired Dr Mike Tanner to design new SNSPD devices aimed at exploiting this effect. Figure 3 shows a prototype SNSPD 'camera' device. The device consists of a single meander wire, but the segments increase in length left to right. This means that the hotspot can only grow up to the length of the segment. The hotspot resistance should vary along the wire leading to a measurement variation in output pulse timing delay. The EOARD funding allowed the PI to purchase ultra low noise amplifiers to achieve the lowest possible timing jitter. The best results achieved so far [15]: via a statistical measurement we can clearly show whether light is focussed on one end of the camera device or the other. In future we hope to achieve single shot discrimination between different regions of the device. In this way we aim to create a SNSPD device with spatial sensitivity in one or two dimensions, suitable for use as a photon counting spectrometer or camera.

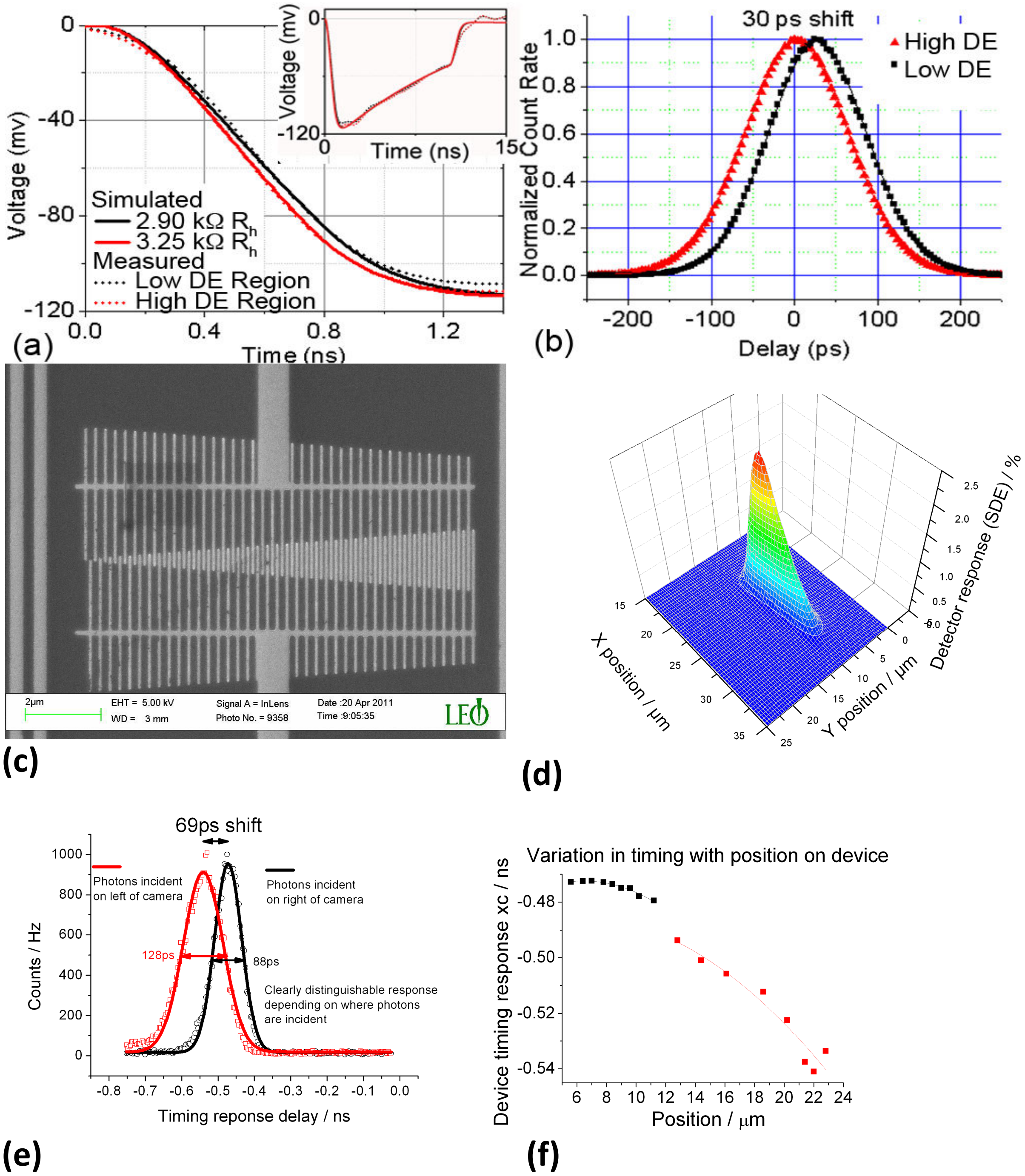


Figure 3 : *(a) variations in hotspot resistance leading to (b) variations in output pulse timing [14]; (c) scanning electron micrograph of 'camera' device uniform wire width but varying segment length (central slim triangular region) ; (d)-(f) first results, showing variation in output pulse timing from one side of the 'camera' SNSPD to the other [15].*

2.3 Testing capability for low energy gap superconductors for improved mid IR sensitivity

Recent work by groups in the at NIST, USA [16] and TU Delft, the Netherlands [17] indicates that low energy gap superconducting materials WSi and NbSi hold promise for mid infrared single photon detection. These superconducting materials are amorphous and can tolerate deposition on a wider range of substrates than more commonly used NbN. The lower superconducting energy gap implies that a nanowire device will have a higher triggering probability on absorption of a mid infrared photon. The main drawback of these materials is the reduced superconducting transition temperature, necessitating sub Kelvin operating temperature. The EOARD award enabled the PI to invest in infrastructure for sub Kelvin device testing for the first time. A novel solution was chosen: a closed cycle ^{3}He stage (a bespoke item manufactured by Chase Cryogenic, UK). This ^{3}He stage can be added to a pulse tube closed cycle cold head (3 K base temperature) to achieve a base operating temperature of 300 mK. The PI and his team (PhD student Peter Saxton) designed a full cryostat to accommodate the ^{3}He stage. This flexible design enables operation of both fibre coupled and miniature microscope coupled superconducting devices.

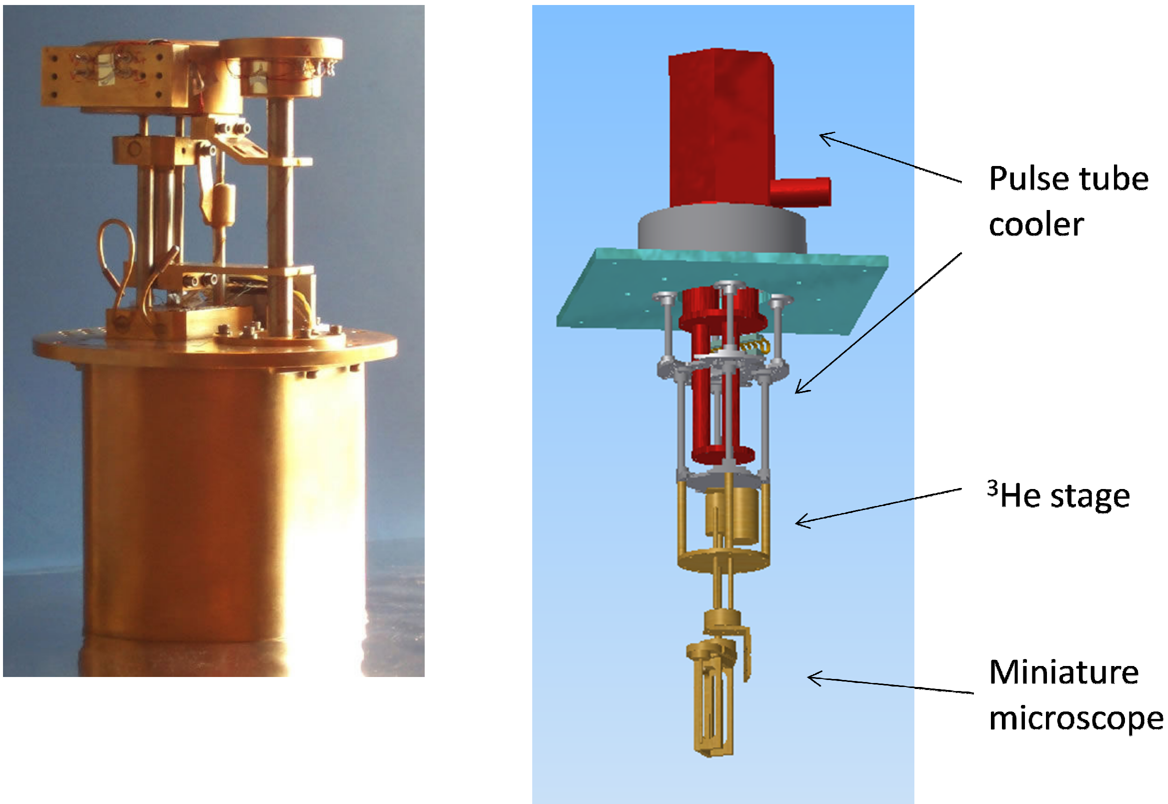


Figure 4: *Sub Kelvin superconducting device testing capability. Left: 3He closed cycle stage (Chase Cryogenic, UK Right: Full cryostat design for ^{3}He stage mounted on pulse tube cooler, target base temperature 300 mK.*

At the time of writing, we are waiting on the completion of cryostat parts from the Heriot-Watt University Workshop. We anticipate assembly and testing of the cryostat in early 2013. The PI will visit Dr Sae Woo Nam's group at the US National Institute of Standards and Technology in Boulder, Colorado, USA to learn techniques for ^{3}He stage operation.

3. DISSEMINATION

The research work in this report is very recent and is principally in preparation for publication [15]. Since August 2011 the PI has published 7 original papers in refereed journals (1 Physical Review Letter, 1 New Journal of Physics, 1 Applied Physics Letter, 2 Optics Express). In addition PI and his team completed a major topical review for the journal Superconductor Science and Technology entitled 'Superconducting nanowire single-photon detectors: physics and applications' [2]. This is the first major review on this field; downloaded >1200 times in the first 3 months since publication.

The funding from EOARD enabled the following conference presentations:

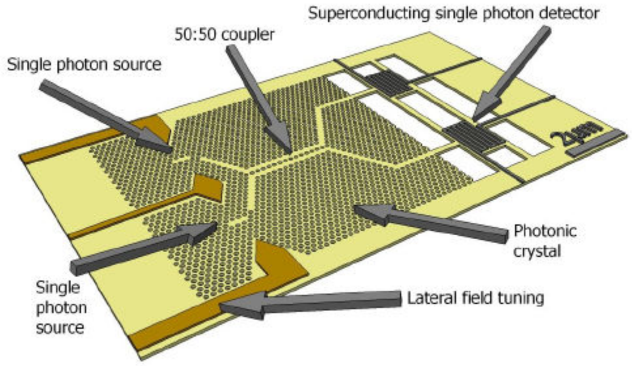
- European Applied Superconductivity Conference (EUCAS 2011) The Hague, The Netherlands, September 2011
- Nanowire Superconducting Single Photon Detector Conference, Eindhoven, The Netherlands, September 2011 (invited)
- Quantum Science Symposium, Boston, USA September 2011 (invited)

The PI also delivered several webcasts on infrared counting technologies:

- National Science Foundation Detector Virtual Workshop, Rochester Institute of Technology, USA, September 2011.
- Laser Focus World Webcast February 2012

4. OUTLOOK

The next year will bring many fresh opportunities. The PI has accepted the position of Professor of Photonics at the University of Glasgow, UK. This will give the PI access to the arguably the UK's best University nanofabrication facility (the James Watt Nanofabrication Centre). The PI will be able to invest for the first time in state-of-the-art sputter deposition equipment, allowing ultrathin superconducting film deposition on substrates up to 3" diameter. This will enable integration of superconducting detectors with integrated waveguide circuits (using well established processes in Glasgow). This is a boost with the PI's newly awarded UK Engineering and Physical Research Council projects: "Semiconductor integrated quantum optical circuits" (in collaboration with the University



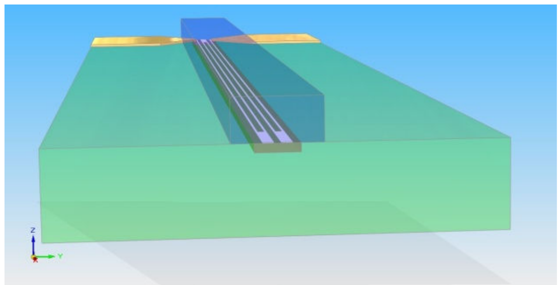


Figure 5: *Upcoming projects. Left GaAs quantum optical circuit with integrated quantum dot single photon source and detector (concept U Sheffield/HWU) Right Waveguide integrated superconducting nanowire single photon detector (concept HWU/U Bristol)*

of Sheffield, UK; PI Professor Maurice Skolnick) and "Lithium niobate integrated quantum photonics" (in collaboration with the University of Bristol, UK; PI Professor Jeremy O'Brien).

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