Superconducting Nanowire Single-Photon Detector Arrays for the Near- to Mid-Infrared

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Abstract—**Superconducting Nanowire Single-Photon Detectors (SNSPDs) are excellent devices for the analysis of faint light from the ultraviolet to the mid-infrared. Recent developments push their broad wavelength bandwidth further into the mid-infrared towards 20 µm and enable new areas of application such as astronomy and chemistry. SNSPDs could play a major role in the field of exoplanet spectroscopy where absorption lines of atmospheric components in the mid-infrared contain a wealth of information. In this work, we present current progress towards optimized detectors for mid-infrared wavelengths and their integration in arrays with the ultimate goal of demonstrating a large scale, single-photon-sensitive mid-infrared camera.**

I. INTRODUCTION

SUPERCONDUCTING nanowire single-photon detectors (SNSPDs) have been developed into a mature technology during the last two decades. Their very high detection efficiency of more than 98% at 1550 nm wavelength [1], dark count rates below 10^{-5} counts per second [2], high maximum count rates of a few megahertz, low jitter down to 3 ps [3], zero readout noise, and their suitability for a broad range of wavelengths from the ultraviolet (UV) to the mid-infrared make them the ideal candidates for a broad range of applications in quantum optics, metrology, astronomy, and chemistry. Recently, there has been interest from NASA in the use of mid-infrared SNSPD arrays for the spectroscopy of exoplanet atmospheres in future space telescopes [4]. SNSPDs are ideal detectors for such an application which requires high efficiency, ultra-low noise, and gain stability of less than a few parts per million. In addition, SNSPDs optimized for mid-infrared wavelengths have been used recently in the field of physical chemistry and vibrational spectroscopy [5]. However, optimizing these detectors for longer mid-infrared wavelengths requires significant materials development to enable high detection efficiency of such low energy photons [6, 7]. Furthermore, the integration of SNSPD pixels into large-format arrays is still at an early stage of development. To date, the largest array demonstrated is 1 kilopixel [8, 9].

An SNSPD consists of a thin film (~5 nm) of superconducting material that is patterned into a meandering nanowire with a width of about 100 nm. The nanowires of an SNSPD can be optimized to absorb photons of a wavelength covering a specific bandwidth by the choice of superconducting material, the nanowire dimensions, and the optical stack with mirrors and dielectrics. The nanowire is operated well below the critical temperature of the superconductor with a bias current on the order of a few microamperes, well below its critical current to keep it in the superconducting state. An absorbed photon can generate a so-called hotspot in the nanowire, which eventually leads to a breakdown of superconductivity in the nanowire and a rapid change (~nanoseconds) in the resistance to ~kiloohms. This detection event diverts the bias current to an amplifier chain for readout until the hotspot cools, superconductivity is restored, and the nanowire is able to detect another photon. When integrated into arrays, heat load constraints place limitations on the number of coaxial cables which can be used for readout. Efficient readout schemes that employ multiplexing or bus readout [7-11] are therefore necessary to develop SNSPD arrays that can be used in telescopes for astronomy or chemistry.

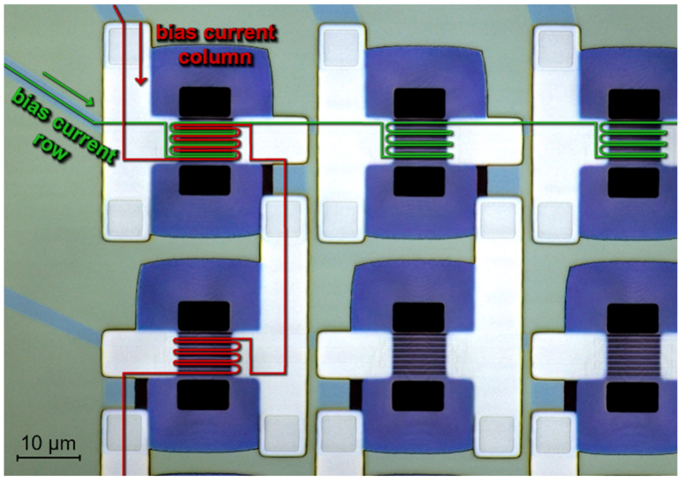

Fig. 1. Photomicrograph of six pixels from the 64-pixel mid-infrared SNSPD array. The row and column SNSPDs are biased separately via two bias leads. The current paths for one row and one column are highlighted.

II. RESULTS

In this work, we combine two multiplexing techniques that have been demonstrated previously: thermally-coupled row-column [11] and a time-of-flight transmission line [9]. This allows all SNSPD pixels to be read out using a total of only six cables, two to bias the row and column SNSPDs and four for the two transmission lines, independent of the size of the array. While the thermally-coupled row-column technique has been demonstrated at 1550 nm, the time-of-flight transmission line has only been demonstrated at UV wavelengths. One of the challenges of multiplexing SNSPDs optimized for mid-infrared wavelengths is the small critical current and operating current, typically on the order of 1 µA [6]. The amount of thermal energy generated when an SNSPD detects a photon is proportional to the square of the operating current. This makes the use of thermally-coupled multiplexing schemes challenging.

A 64-pixel SNSPD array was fabricated in the NIST Boulder Microfabrication Facility in this work. A 5 nm-thick film of a mid-infrared-optimized composition [6] of the amorphous superconductor tungsten silicide (WSi) was used for the SNSPDs. The pixels are arranged on a 30 µm pitch for both the

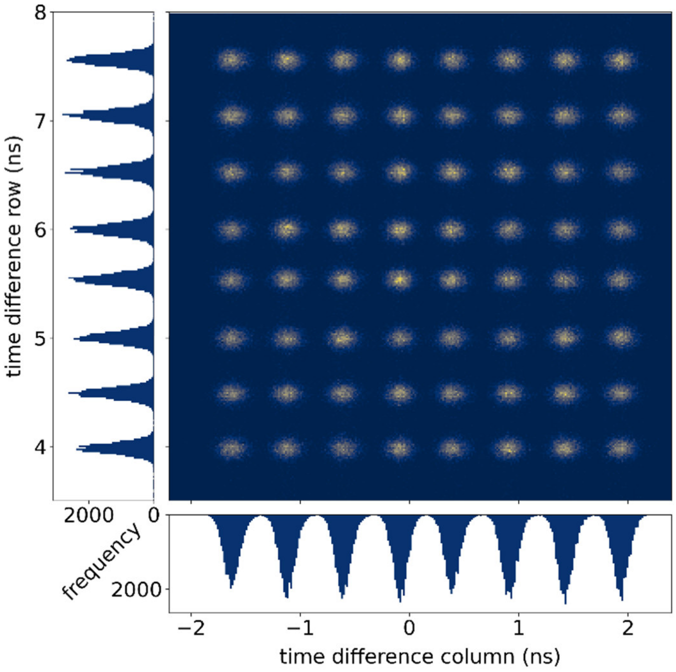

Fig. 2. Measurement results for a 64-pixel mid-infrared SNSPD array. Shown are 1D and 2D histograms for the time tagged data.

rows and the columns. Each pixel of the array consists of two interleaved SNSPDs on a 200 nm thick SiO_2 membrane to enhance thermal coupling between them. All SNSPDs in a single row or column are wired in series through one large inductor for each row or column, while all rows are biased in parallel through one lead, and all columns through another lead. The inductors are designed to provide enough energy to couple detection events thermally to the transmission lines for readout as described below. A photomicrograph of the fabricated device is depicted in Fig. 1. The current flow for one row and one column is highlighted in green and red, respectively.

A photon detection event on either the row or column nanowires, which are co-wound within a single pixel, will create hotspots in both due to thermal coupling. The bias currents from both the row and column nanowires are then diverted into constrictions where they are thermally coupled to readout transmission lines. Each transmission line, which is patterned in the same WSi layer as the SNSPDs, is also biased with a bias current. The constriction heats up and causes a breakdown of superconductivity in the transmission line. The sudden resistance change leads to a positive pulse, which travels in one direction, and a negative pulse, which travels in the other. The origin of the voltage pulses along the length of the transmission line can be derived by the different arrival times at each end of the transmission line. The corresponding pixel is then determined by correlating the positions along the length of the row and column transmission lines.

The measurement of the SNSPD array was performed in an adiabatic demagnetization refrigerator (ADR) at a temperature of 350 mK. The array was flood illuminated via a fiber from an attenuated, fiber-coupled laser at a wavelength of 1550 nm. The SNSPDs were biased via the dc ports of two bias-tees with a current of about 4.1 µA for each row and each column. Each transmission line was biased via the dc port of a bias-tee at 2.9 µA. The other end of each transmission line was also connected to a bias-tee and the dc port was 50 Ω terminated. The ac ports of all four transmission line bias-tees were amplified with a total gain of 44 dB and connected to a time tagger.

Measurement results for the 64-pixel array for a 10 s long measurement are depicted in Fig. 2. The time differences of the arrival times on each end of the transmission line are shown as histograms for the row and the column separately and as a combined color-coded 2D histogram. It can be seen that each pixel is very well separated by about 0.5 ns with a FWHM of below 160 ps for each peak. Further characterization of the SNSPDs showed a large plateau with saturated internal efficiency of the detectors as a function of bias current for 1550 nm photons. Measurements at longer wavelengths extending into the mid-infrared showed saturated internal efficiency for wavelength up to 5.2 µm.

III. SUMMARY

In this work, the development of a 64-pixel SNSPD array with a thermally-coupled readout scheme for the mid-infrared was presented. The promising measurement results for light at a wavelength of 1550 nm are the starting point for the optimization of the presented design for longer wavelengths and larger array sizes.

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