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Electron doped superconducting cuprates for photon detectors☆

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ABSTRACT

The study of unconventional materials with peculiar properties is a fundamental step for the design and advancement of superconducting photon detectors. $Nd_{2-x}Ce_xCuO_{4\pm\delta}$ is a non-traditional cuprate superconductor exhibiting n-type conduction which properties can be changed by modifying its cerium and oxygen content. Ultra-thin films of this compound have been deposited by dc sputtering technique, and systematically characterized by using X-ray diffraction and electrical measurements. Design and patterning of sample geometries have been performed by optical and electron beam lithography in order to obtain sub-micron wide strips for measurements of photon detection.

1. Introduction

In recent years single-photon detectors have come across a wide range of applications in various research field. They can be used in quantum communication networks as the most critical elements to determine the performance of several civilian and military systems. They also play a vital role in optical telecommunication in the cosmic space as well as in quantum optics experiments. In addition, single photon detectors are used for applications including bioluminescence detection, DNA sequencing, Förster resonance energy transfer (FRET) for studying protein folding, light detection and ranging (LIDAR) for remote sensing, optical time domain reflectometry, picosecond imaging circuit analysis, single-molecule spectroscopy and fluorescence-lifetime measurements, medical applications such as diffuse optical tomography and positron emission tomography, and finally applications such as traditional and quantum-enabled metrology [1].

Single-photon detectors based on superconducting nanowires (SSPDs or SNSPDs) have rapidly emerged as a highly promising photon counting technology for infrared wavelengths. These devices offer high efficiency, low dark counts and excellent timing resolution. Superconducting materials have indeed special properties, which make them extraordinarily appealing for electronic applications [2].

A zero dc resistance, a complete diamagnetic response developed in the presence of a static magnetic field and macroscopic quantum phenomena are the peculiar properties of the superconducting state. In particular, in a superconducting material below a critical temperature, T_c, electrons tend to form bounded pairs (Cooper pairs) and current can flow without Joule heating (zero resistance) up to a maximum current defined by the critical current density, J_c [3,4]. The superconductors can be divided into two main categories: conventional, or low-T_c, and unconventional, or high-T_c superconductors (LTS and HTS, respectively). At the first class belong all the superconductors known until 1986, when the discovery of high-T_c superconductivity opened new perspectives in the application of these materials [5–7]. In particular, in the field of sensors, as these materials are sensitive to incident radiation at optical wavelengths, LTS materials have been used as radiation detectors. This has been made possible from the advent of suitable technologies for the deposition of thin films and micro- and nano- fabrication of geometries useful for sensors [8]. One disadvantage of superconductors is the need to maintain the samples at very low temperatures, and to bring electromagnetic signals to and from the room temperature environment. The expensive liquid helium is being replaced by compact, low power, user-friendly cooling systems since the discovery of HTS.

In this work we have fabricated ultra-thin films of the electron-doped compound $Nd_{2-x}Ce_xCuO_{4\pm\delta}$ (NCCO) by a dc sputtering technique. The samples have been characterized by X-ray diffraction technique to control the quality of the films and by current-voltage

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characteristic and resistivity as a function of temperature measurements to check the superconducting properties. On the other hand, femtosecond optical pump-and-probe measurements performed in previous works [9,10] on similar NCCO films, demonstrate a faster response of this compound (~1 ps) respect to HTS devices. Optical and electron beam lithography have been optimized to pattern the films in a four contacts microbridge geometry for photon detection measurement tests.

2. Superconducting photon detectors

Optical photon detectors based on superconducting films with excellent performance at radiation wavelengths ranging from ultraviolet to infrared have been recently developed.

The performance of such detectors is mainly determined by the system detection efficiency, defined as the probability of measuring an output electrical signal due to an effective incident photon, the dark count rate associated to the probability to measure an output signal even in the absence of incident photons, and the timing jitter measured by the time delay between the absorption of a photon and the recording of the output signal. Very high system detection efficiency up to 90%, low dark count rate and improved timing jitter have been reached in practical devices in the recent years. Another important characteristic is the repetition rate, which is the time required between two consecutive photodetection events. This can be very high due to values in the picosecond range of the recovery time.

In a superconductor, the energy required to break a Cooper pair with the resulting creation of two quasiparticles, is extremely low (few meV) and about three orders of magnitude smaller than the energy gap of a typical semiconductor (1.12 eV for Si). Consequently, the absorption of a single optical photon can create a large number of excited quasiparticles, improving the energy resolution of superconducting detectors [11,12]. Furthermore, the cryogenic operation temperature assures very low signal-to-noise ratio in the measured output voltage of the device. SNSPDs consist of ultrathin (few nanometers) superconducting strips with a very narrow-width, less than 100 nm. A meander type geometry is typically used in order to achieve high coupling efficiency of the detector with the photons source. Other geometries based on a parallel connection of ultrathin nanowires have also been used [13].

In Fig. 1 the mechanism of photodetection is shown. A superconducting strip detector operates at a temperature well below the critical temperature and under a dc current bias, I_b, just below the critical current, I_c. The absorption of a photon with energy $h\nu >> 2\Delta$, being Δ the binding energy of a Cooper pair, leads to a local suppression of superconductivity (photon-induced hotspot, the circle in the sketch of Fig. 1) and therefore to a current redistribution in the strip [14]. As a result, where the bias current exceeds the local film critical current value, a section of the film becomes normal. At this point, the Joule heating, due to the current passing through the resistive section, generates an avalanche mechanism that ultimately makes the whole strip resistive. As a consequence, a voltage pulse of picosecond time scale is generated. After a characteristic time (tenths of picoseconds), that depends on the relaxation processes involving phonons, quasiparticles and Cooper pairs and on cooling efficiency (the phonon escape time), the heat is removed from the film, leading to the restoring of the superconductivity. A simple phenomenological model has been used to describe the experimental behaviour of such device. This model is based on the equivalent circuit shown in Fig. 2 involving an inductor L representing the kinetic inductance of the superconducting strip, a current source I_b, a load impedance Z_L, a switch controlled by the hot spot formation and a resistor R_n simulating the normal state resistance of the superconducting line.

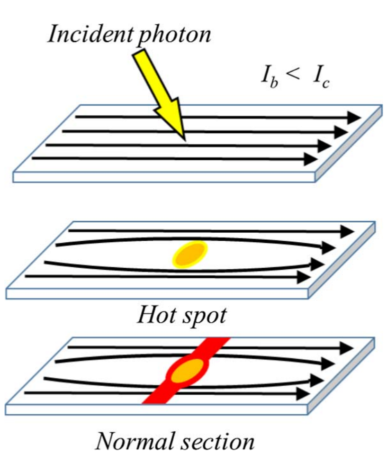

Fig. 1. Resistive section of a superconducting strip induced by an incident photon through a hot spot formation.

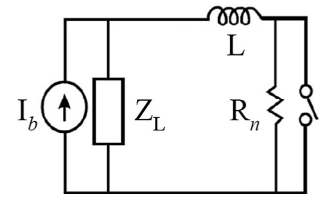

Fig. 2. Equivalent circuit of a superconducting photon detector.

The role of the superconducting material is crucial, since its parameters determine the performance of the detectors. In fact, the inductance L depends on the geometrical factor of the device and on the superconducting penetration length λ, the normal state resistance R_n must be much greater than the external load impedance Z_L, and the critical current I_c, sets the limit of the bias current and determines the minimum photon energy resolved by the detector.

The intrinsic photoresponse of a superconducting strip detector is determined by the energy-relaxation time constants of the different systems of particles existing in the device: Cooper pairs, electrons from broken Cooper pairs (quasiparticles), phonons in the films and in the substrate. In ultrathin superconducting films, these relaxation times can be in the picosecond range assuring very high repetition rates up to the GHz range.

The intrinsic photodetection mechanism in superconductors is still far to be completely understood and other possible mechanisms, based for example on vortex-assisted photon detection or on the quasiparticles diffusion, have been recently reported in the literature [15–17]. From engineering point of view, methods to increase the photons absorption efficiency and the optical coupling are under investigation [18–23].

Pump-probe experiments are generally performed to investigate the relaxation dynamics in superconductors, but other techniques like for example the vortex instability jump analysis in current-voltage characteristics have also been reported [24].

3. Superconductive materials

Both LTS and HTS materials can be used for application as detectors. The photoresponse of LTS and HTS materials has been measured and reported in literature. In particular, ultrathin niobium nitride (NbN), a LTS with $T_c \approx 17$ K, is the material of choice for the best SNSPDs reported in literature, because it remains superconducting even if structured into nanostrips, has fast photoresponsive properties (~30 ps) and is compatible with standard superconductive electronics technology [25–27]. While NbN was originally the first material used for SSPDs many other materials were tested during the past years such as Nb, NbTiN, TaN, MgB_2, NbSi, $W_x Si_{1-x}$, and $Mo_{0.75}Ge_{0.25}$ [28]. For these materials optical response and fabrication of nanowire detectors have been investigated demonstrating single photon sensitivity and, in some cases, improved optical coupling and better system detection efficiency