Photoresponse experiments on NbN proximized nanostructures

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Abstract. Among superconducting materials used in developing high performance nanowire detectors, NbN demonstrated to have unique characteristics in terms of fast response time, quantum efficiency and photon-number resolving capability. We investigated the role of proximity effect on superconducting NbN thin films covered by a weak ferromagnetic NiCu thin layer. Hetero-structures NbN/NiCu have been deposited by DC magnetron sputtering on MgO substrates without any heating. Characterization in terms of morphological, transport, and ultra-fast optical properties has been done. Superconducting nanowires with meander-type geometries (48 micron lengths and <500 nm widths) have been designed and fabricated. Preliminary results concerning their photoresponse to 1550nm laser irradiation are presented.

1. Introduction

Optical detectors are used in several applications spanning from telecommunication to spectroscopy, monitoring, imaging, ranging, etc. The performance of photodetectors is typically measured in terms of sensitivity in detecting single photons, response time, spectral response, and array integration capability. The limited detection efficiency, dark count rate and dead time strongly depend on the wavelength range of interest: while very good detectors exist in the visible range, based on an optimised silicon technology, poor performance is obtained in the infrared (IR). Recently, a new class of superconductive devices, named Superconductive Single Photon Detectors (SSPD), has been proposed with promises of very good performances as single photon detectors. SSPDs are based on the so-called "hot-spot" mechanism [1, 2]: the absorption of a single photon in a narrow superconductive stripe creates a resistive hotspot, i.e. a local nonsuperconducting region. If the superconductive stripe has nanometric size (typically a width of 100 nm and thickness of few nm) and is initially biased with a DC current close to its critical value, then the supercurrent avoids the hot-spot and accumulates towards the edges of the stripe. Here the critical current density may be reached, producing a voltage pulse detectable by the front-end electronics. Hot-electron relaxation processes bring the film back to the superconducting state in a time of the order of tenths ps [3], allowing an extremely low jitter [4], operating frequencies well above 1 GHz, and large detection efficiency [5]. The material used in the realization of a SSPD is niobium nitrate (NbN) because of its high critical temperature (Tc=16K), short coherence length (ξ=4-5nm), and short
electron-phonon characteristic time (~10ps) [6]. The time response of superconducting detectors is related to the non equilibrium processes which take place after the photon absorption, and restore again equilibrium inside the perturbed material. The incoming radiation breaks Cooper pairs and directly heats up the electron gas (hot electrons). They relax down in energy through the electron-electron and electron-phonon interactions, resulting in a temperature increase of the electron subsystem. Relaxation processes depends on the choice of material, and thus it is crucial to investigate the non equilibrium dynamics of the carriers for optimizing the photo-response of realized devices. Recently, promising results in terms of fast photoresponse of micro-bridges formed by Nb/NiCu thin layers have been obtained [7], demonstrating that the superconducting properties of the bilayer can be artificially controlled by the presence of proximity effect between the superconducting and the normal layer.

Recently, tunable femtoseconds-pulsed lasers opened new possibilities of directly studying fundamental, nonequilibrium electronic processes such as electron-phonon interaction in various materials. Recently the femtosecond pump-probe spectroscopy experiments, by using solid-state, tunable lasers with high repetition rates and the pulse width less than 100 fs, have been widely applied to study fundamental aspects related to nonequilibrium carrier dynamics physical problems in different materials largely used in electronics and optoelectronics [8]. The pump-probe technique is an optical sampling on a perturbed area by fast laser pulses: in particular, a high-intensity pump beam excites the sample, while a low-intensity probe beam, optically delayed with respect to the pump beam, measures the nonequilibrium state through the change of its physical property e.g. amplitude, polarization, etc. In this way, by monitoring the change of an optical property of the perturbed material, (for example reflectivity) as a function of the delay time between beams, relaxation times involved in the equilibrium restoring can be measured.

In this paper we report on the optical response of heterogeneous nano-layers formed by NbN thin films overlayed by ferromagnetic NiCu thin layers. Optical ultrafast pump-probe (100fs pulse width) have been performed to study the influence of the proximity effect on dynamics of excitations in the first picoseconds after the laser pulse absorption, and down to low temperatures (3K). Superconducting nanowires with meander geometries (48 micron lengths and <500 nm widths) have been also realized, and preliminary results in terms of their photo-response to 1550 nm laser irradiation are also presented.

2. Experiment

2.1. Sample Fabrication

Thin films of both superconducting NbN and ferromagnetic Ni$_x$Cu$_{1-x}$ alloy (x~0.6) have been deposited by dc magnetron sputtering in a ultra-high vacuum system. The base NbN layer was grown on a single crystal MgO (110) substrate without any additional heating in a mixture of Ar and N$_2$ pressure of 0.8 Pa (flow Ar= 80 SCCM and flow N$_2$=1.2 SCCM) with a system base pressure of 2 $10^{-5}$ Pa. The sputtering power density and the deposition rate were 4.59 W/cm$^2$ and 30 nm/min, respectively. The NiCu overlayer was deposited at a deposition rate of 60nm/min (power density of 0.9W/cm$^2$). The dependence of the critical temperature of NbN thin films as a function of the thickness has been reported in Ref. [9]. In view of photoresponse experiments, the thickness of NbN has been fixed at $d_{\text{NbN}}=8$ nm with a resulting base critical temperature $T_c(\text{NbN}) = 13$K. The thickness of the NiCu overlayer ranges from 3 nm to 12 nm: the lower limit was due to some limitations in the thickness monitoring. NbN and NbN/NiCu thin films have been patterned with a meander-type geometry consisting of six blocks of three parallel lines as showed in figure 1a. The nanosizing of realized devices has been obtained by Electron Beam Lithography (EBL). The line width ranges from 150nm to 500nm, the length of each line is 20 µm, while the device covers an area of about 20 x 20 µm$^2$. A photograph of a realized device is proposed in figure 1b.
2.2. Fast reflectivity pump-probe measurements

In pump-probe experiments, the output of an ultra-fast, mode-locked, Ti:sapphire laser operating at 800nm wavelength is divided into two beams. One beam (pump) is used to excite the sample, and due to its short (~100 fs) duration, it acts as a delta-function-type excitation. The second beam (probe) probes the changes in reflectivity induced by the pump, as a function of the relative time delay to the pump beam. The pump and probe beams are cross polarized to eliminate coherent artifacts due to the interference of the two beams. The probe beam is much weaker than the pump beam (usually their ratio is 1:10) in order to ensure that the changes in the material are induced only by the pump. In particular, in these experiments the fluence in presented experiments was <100 μJ/cm² for the pump.

![Figure 1](image1.png)

**Figure 1.** (a) Design of the 6 in-series blocks of 3 parallel lines with 150nm width; (b) Optical image of the realized device.

![Figure 2](image2.png)

**Figure 2.** Reflectivity change of a NbN(8nm)/NiCu(12nm) (square), and pure NiCu (6nm) (circle) measured at T=3K. The NbN surface was cleaned by low energy ion beam before NiCu deposition. The line is an exponential fitting of data.
Femtosecond spectroscopy allows us to study the dynamics of electrons and the electron-phonon interaction with sub-ps resolution. The samples are mounted on a cold finger in a temperature-controlled liquid-helium continuous flow cryostat equipped with an optical window and operating down to 2.7 K. The pump and probe beams are focused down to 30 \( \mu \)m diameter spot onto the sample. A detailed description of the experimental pump-probe apparatus can be found in Ref. [10]. Briefly, photons from the pump beam are absorbed by conducting electrons inside the superconducting absorber: these high-energy electrons (photoexcited electrons) thermalize with the other electrons almost instantaneously (<10fs), creating hot electrons with a higher electron temperature. Afterwards, these hot electrons relax through electron-phonon interaction, and thus produce a change in the phonon temperature. Finally, hot phonons release their energy to the substrate. Figure 2 shows the typical differential change of reflectivity in a superconducting NbN(8nm)/NiCu(12nm) bilayer measured at \( T = 3K \). The reflectivity signal is mainly characterized by a long relaxation time (>10 ps) we ascribe to the proximity effect between different layers which influences the specific heats of electron and phonon subsystems, and thus the relaxation processes. This behaviour was confirmed also in other samples with different NiCu thickness. At \( T > T_{cs} \), where \( T_{cs} = 6K \) is the superconducting critical temperature of the bilayer, the \( \Delta R \) signal is dominated by the metallic optical response of pure NiCu, with an electron-phonon relaxation time of about 2ps.

2.3. Photoresponse experiments

Devices have been characterized in terms of current-voltage characteristics (IVCs) at low temperatures. The critical currents \( I_c \) were found to be 17.5 \( \mu \)A and 8 \( \mu \)A for NbN/NiCu and pure NbN devices, respectively. Moreover, the overall response to a laser with a wavelength of 1550 nm operating in continuous way (1 mW) has been also tested. Results both for pure NbN and NbN(8nm)/NiCu(3 nm) with and without the laser illumination are reported in figure. 3.

![IV characteristics at T=4.76 K for a pure NbN (triangles) and a NbN/NiCu (squares) devices without and with laser illumination (the laser reduces in both cases the currents).](image-url)

**Figure 3.** IV characteristics at \( T = 4.76 \) K for a pure NbN (triangles) and a NbN/NiCu (squares) devices without and with laser illumination (the laser reduces in both cases the currents).
Preliminary photoresponse experiments have been performed. The nanowires are biased at a current $I_b$ slightly below the critical current $I_c$. The dc bias is realized through a twisted pair ending with a “T” type RC filter (BW few kHz) used for both noise reduction and ac/dc decoupling. High frequency signals resulting from laser absorption are transmitted to readout electronics by a 50$\Omega$ coaxial cable (3 GHz). A room temperature amplification of photoresponse signals up to a gain of 400 has been obtained by wide band (from few KHz to 2 GHz) RF amplifiers AC coupled to the coaxial cable. Finally, the output is connected to a 6 GHz bandwidth oscilloscope for waveforms acquisition. Optical excitation is through a laser diode with $\lambda=1550$nm, output power 1mW, pulse duration 20ns, and repetition rate 10MHz.

By comparing the photoresponse signals from both pure NbN(8nm) and NbN(8nm)/NiCu(3nm) meander devices, measured at $T=4.8$K, we observe that for sole NbN the amplitude is about one order of magnitude smaller than the proximized device. In spite of different critical currents, the ratio between the bias current and the critical current was almost the same, i.e. $I_b/I_c=0.8$ while the ‘normal’ resistances for the two devices were about 46k$\Omega$ and 65k$\Omega$, respectively.

3. Conclusions
We have fabricated and tested superconducting NbN and proximized NbN/NiCu nanowires at low temperatures under laser illumination with $\lambda=1550$nm. We found that the presence of a NiCu thin overlayer modifies the electron-phonon dynamics during the initial energy cascade resulting in longer relaxation times with respect to the case of a pure NbN film as reported in ref. 6. Moreover, the photoresponse experiments performed both on pure NbN(8nm) and NbN(8nm)/NiCu(3nm) nanowires in meander-type geometry showed an increase of the signal amplitude in the presence of proximized samples. Since NbN is the most used material for the development of advanced superconducting single photon detectors, these studies appear interesting both for fundamental aspects involved in the nonequilibrium physics in the presence of unconventional proximity effect and potential search for new solutions able to enhance detector performances.

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