SCIENTIFIC REPORT ON STM 2013 ACTIVITY

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The research program of Dr. Jürgen Lisenfeld was dedicated to the implementation of NbN material in superconducting Josephson phase qubits and comprised the following activities:

-Improvement of the circuit design of superconducting Josephson phase qubits which consist of an rf-SQUID coupled to a flux bias coil, microwave line and readout dc-SQUID.
-Adaptation of the qubit design for its realization with the NbN technology established at the ICIB-CNR.
-Fabrication of qubit devices in NbN-based technology at the ICIB-CNR.
-Joint experiments performed at ICIB-CNR to characterize at liquid helium temperature both NbN-based qubits fabricated at ICIB-CNR and Nb based qubits of the Karlsruhe Institute of Technology (KIT), Karlsruhe.
-Optimization of the ICIB-CNR experimental set-up as well as the software for data acquisition and data analysis.

This project was motivated by recent findings that the presence of parasitic defects, so-called Two-Level-Systems (TLS), leads to noise and decoherence in a variety of nanotechnologically fabricated devices, such as for example quantum bits, microwave resonators, single-electron-transistors or single photon detectors. The nature of these defects is not yet understood, but they are assumed to behave like atomic-sized electrical dipoles which are residing in oxides on the surfaces of metallic wiring layers and, most importantly, also in the tunnel barriers of Josephson junctions. It has been shown that quantum bits can be strongly coupled even to single defects which themselves behave as quantum TLS's which can resonantly exchange photons with qubits or resonators, leading to decoherence [1]. It is therefore mandatory to thoroughly understand the physics of TLS in order to improve qubit coherence times by avoiding their occurrence through appropriate fabrication methods. Figure 1 shows a sketch of the different models that were suggested for TLS in a Josephson junction environment, together with the circuit schematic of the phase qubit circuit that is used for this project.

So far, nearly all qubits were fabricated with Josephson junctions that employ amorphous aluminum oxide as tunnel barriers. This amorphous oxide is known to host large densities of detrimental TLS. Within this project, we aimed at fabricating for the first time Josephson phase qubits that use tunnel junctions with a AlN barrier. A lower TLS density for these materials would directly translate in longer coherence times; moreover, comparing the defect properties in samples made from different materials would furthermore greatly assist the understanding of how TLS emerge in fabrication. The resonant qubit-TLS interaction in fact allows one to operate single TLS in the coherent quantum regime, and their coherence times can be measured using standard NMR-like pulse sequences such as Ramsey interference or Rabi oscillation measurements. The qubit coherence time does not need to be longer than a few tens of nanoseconds in order to resonantly address individual TLS, which is why we can utilize a relatively simple phase qubit circuit for the goal of studying the defect properties.

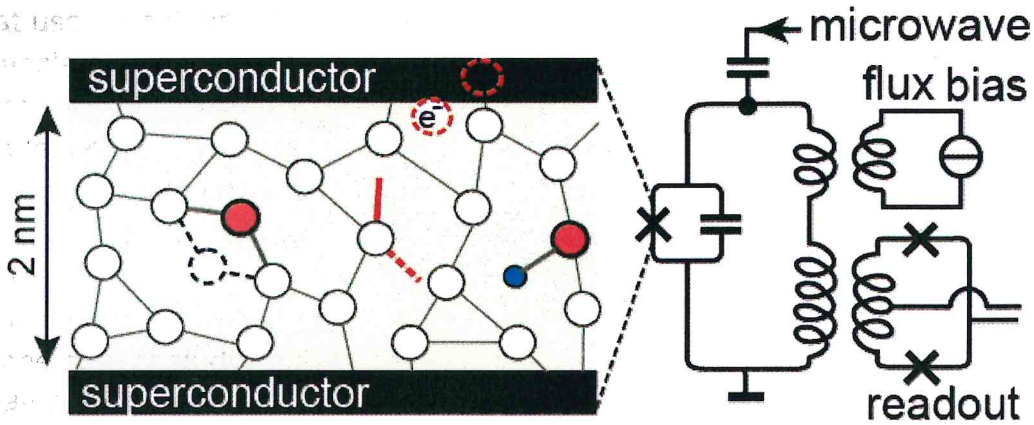

Figure 1. A sketch of a Josephson junction, consisting of two superconducting electrodes separated by a thin layer of amorphous oxide. Different TLS models are indicated: TLS due to single atomic tunneling; single electrons being trapped at the electrode interface; dangling bonds; or alien atoms such as hydroxide defects contributing a motional degree of freedom. The right schematic shows the phase qubit circuit used in this research project.

To meet above quoted central goals in the assigned time, a new circuit design and a set of photolithography masks were prepared before arrival to Italy. The layout of the new qubit circuits was based on the last version of the Josephson phase qubit device fabricated at the Hypres foundry in their standard Nb-based fabrication process. The phase qubit's circuit schematic is shown in Figure. 1. The qubit's Josephson junction was embedded in a rectangular loop of size 55 x 84 μm^2 to form the rf-SQUID. The size of the qubit loop was chosen to result in a suitable β_L – parameter, which is determined by the critical current of the qubit Josephson tunnel junction and the loop inductance. The microwave transmission line for resonant qubit excitation was designed in coplanar configuration as a 6 μm wide central conductor separated from the ground planes by 4 μm. The central conductor was interrupted by a coplanar dc-break capacitor. As to the ground configuration, two types of devices were projected: one of them had a direct electrical connection of the microwave ground to the qubit Josephson junction, while in the other type the qubit was galvanically isolated from the microwave line by means of an interdigitated capacitor. The size and position of the readout dc-SQUID loop were optimized to obtain a sufficiently large mutual inductance to allow detection of the qubit's flux state. The readout dc-SQUID was designed such that noise in its bias current does not couple to the qubit. For this aim, two identical Josephson junctions were connected in series in one branch of the SQUID, while a single junction was included in the other branch. The areas of each of the two junctions connected in series were twice as large as the area of the single junction. With this configuration, the SQUID's bias noise becomes decoupled from the qubit by tuning the dc-SQUID bias current until the inductances of both branches become equal, resulting in a vanishing mutual inductance between the dc-SQUID and the qubit. Concerning the wiring insulation, the initial qubit design realized with Hypres technology utilized a Nb anodization process and additional deposition of amorphous SiO_2 fully covering the device structure. Since the high density of microscopic TLS's in the amorphous insulation materials is considered to be a dominant source of decoherence for superconducting qubits, in our improved qubit design we patterned the wiring insulation using a lift-off process only where it was absolutely necessary in order to improve the coherence time. The anodization process was avoided from the fabrication of the NbN based qubit devices. The mask layout of the improved qubit design was drawn by the CleWin software and the set of photolithography masks for fabrication of new qubit devices were fabricated both at ICIB-CNR and at KIT.

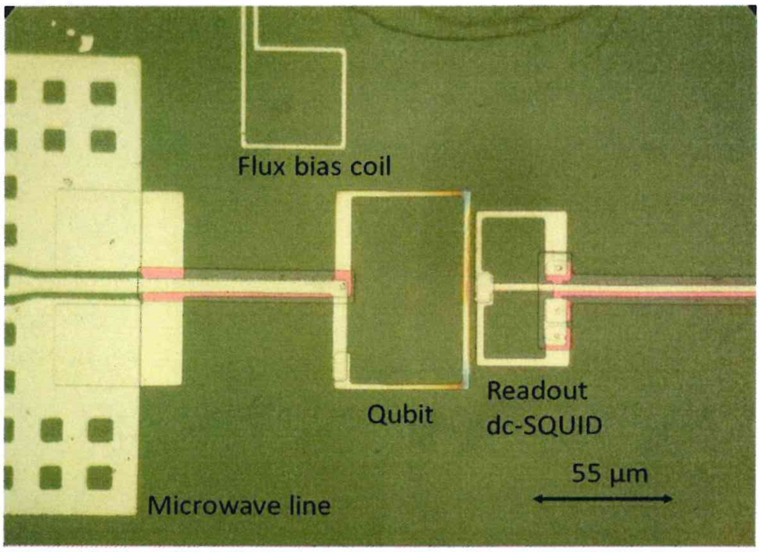

Figure 2. Optical microscope photograph of the NbN/AlN/NbN Josephson junction phase qubit circuit fabricated in the improved design at ICIB-CNR.

The improved qubit devices were fabricated with the NbN-based technology at the ICIB-CNR. The NbN(200 nm)/AlN(3 nm)/NbN(60 nm) trilayer was deposited at room temperature on an M-plane sapphire substrate in the MRC load-lock cryovacuum deposition system. The NbN bottom and top electrodes were made by dc-magnetron sputtering from an Nb target in Ar/N_2 atmosphere. The AlN barrier was deposited by dc-magnetron sputtering from an Al target in N_2 atmosphere. The first photoresist mask defining junction areas was patterned by conventional contact photolithography and the junction areas were defined by Reactive Ion Etching in an O_2+CF_4 plasma. The bottom NbN electrode was patterned by Reactive Ion Etching in O_2+CF_4 plasma after conventional contact photolithography. The wiring insulation SiO layer was deposited with the thermal evaporation technique and its geometry was defined by a lift-off process. Small diameters of Josephson junctions required the use of laser beam photolithography to pattern the photoresist for SiO lift-off. As a last technological step, the NbN wiring layer of thickness 400 nm was deposited by dc-magnetron sputtering and patterned by a lift-off process. Figure 2 shows an optical microscope picture of the phase qubit circuit employing NbN/AlN/NbN Josephson junctions, fabricated in the improved design.

Several Josephson phase qubits fabricated at Hypres foundry were characterized at T=4.2 K using the experimental setup at the ICIB-CNR. In these measurements, we recorded switching-current statistics of the readout dc-SQUID (I_c) and their dependence on the external bias magnetic flux (ϕ) applied by the on-chip flux bias coil. First measurement runs were carried out using the original electronic setup that featured low temperature low-pass RC filters which had been already installed before the STM visit. Initial measurements with these previous filters revealed high levels of low-frequency noise reaching the sample.

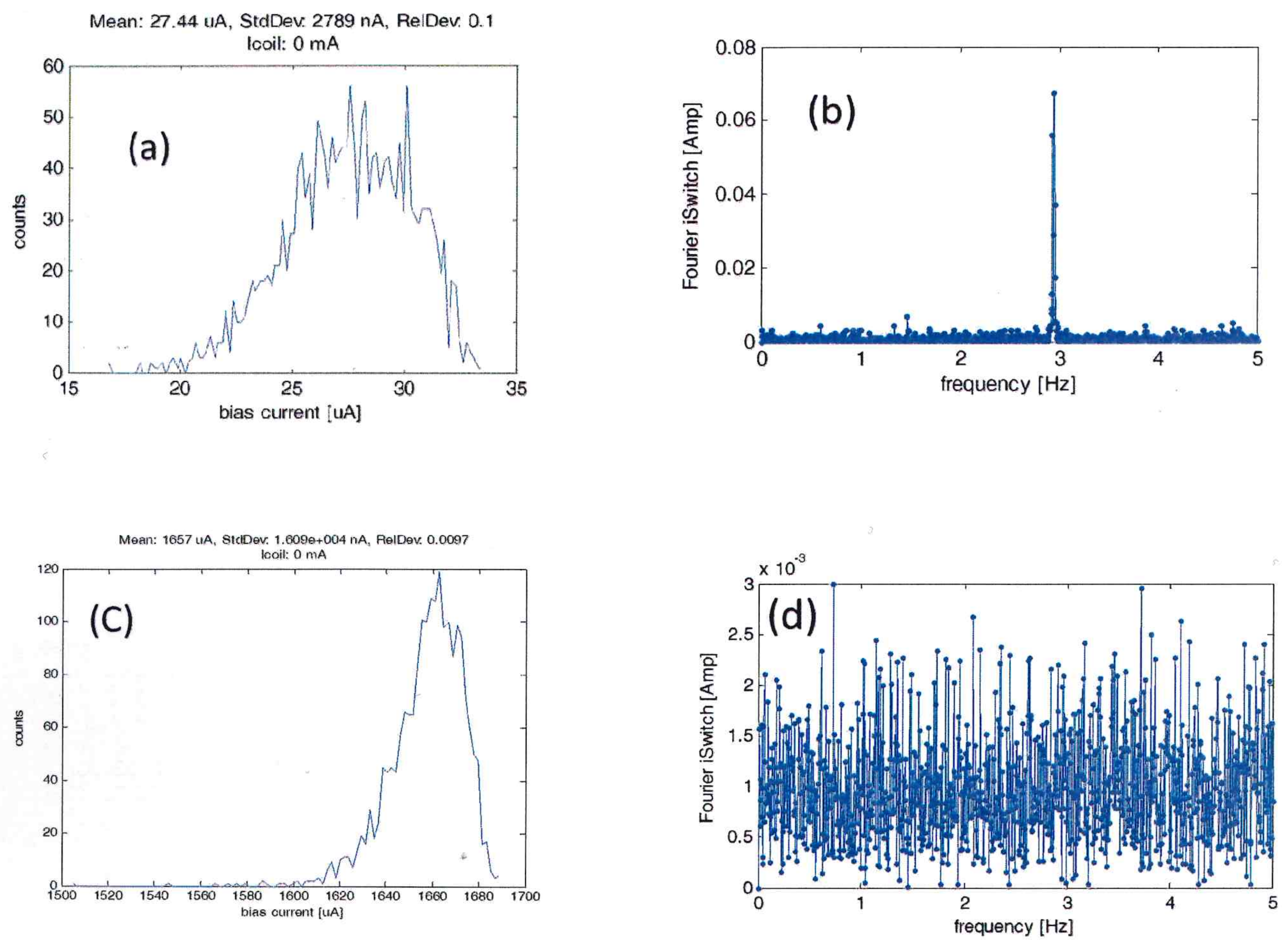

Figure 3. Noise test measurements for qubit HypA. (a) Switching current distribution at zero bias magnetic flux measured by the experimental setup with the original filter configuration. (b) Fourier transform of the $I_c(t)$ dependence utilized for construction of the histogram (a), revealing a dominant low-frequency noise component. Figures (c) and (d) show corresponding data obtained on the same sample after installation of improved filters. In (c), the current axis appears scaled by the current-divider factor of about 55.

This noise almost completely masked the characteristic steps on the $I_c(\phi)$ curve which are caused by the qubit undergoing transitions between potential wells at certain values of external flux.

Figure 3 (a) shows a typical switching current distribution at zero bias magnetic flux recorded for sample HypA. This histogram is characterized by a distorted peak shape, suppressed mean switching current (~27 μA) and a broad histogram width of 2.8 μA. The Fourier transform of the $I_c(t)$ dependence related to the histogram of Figure 3(a) revealed the presence of noise at a frequency of around 3 Hz (Figure 3 (b)). The origins of this low frequency noise presumably are currents flowing in ground loops in the room temperature electronics as well as interference from mains-powered equipment like the oscilloscope or computer. Its low frequency results from down-conversion of the 50 Hz mains interference with the experimental rate of measurements of typically a few tens of Hz. In order to reduce this noise, a low temperature current divider of factor 55 was inserted in the current line of the readout dc-SQUID after the low-pass RC filters. In addition, the low-pass RC filters in the voltage line were exchanged with low-pass RC filters in a new configuration. Both filters were successfully tested at KIT in experiments on qubit devices [2]. The installation of the new filters in the readout dc-SQUID wiring reduced drastically the sensitivity of the dc-SQUID measurements to external noise. Indeed, the switching-current histogram became 10 times more narrow (~0.29 μA) and its mean critical current was higher (~30 μA) when the new filters and current divider were used (see Figure 3(c)). Figure 3 (d) shows the Fourier transform of the $I_c(t)$ dependence corresponding to the experimental data of Figure 3(c). The Fourier transform clearly confirms an improvement of the noise situation after modification of the filters: in contrast to the previous filter configuration, no distinguished peaks were observed and only Gaussian random noise remained in the measurement setup.

As conclusions, an important motivation of this project is to understand the physics of the ubiquitous defects that are residing in tunnel barriers of Josephson junctions in order to reduce their detrimental impact which affects a large variety of nanotechnologically fabricated quantum devices. A central aim was thus to fabricate first qubits which utilize NbN tunnel junctions in order to compare their properties such as defect densities and coherence times to the commonly used AlOx-based qubit junctions. The circuit design of superconducting Josephson phase qubits was improved. It further was adapted for device realization with the NbN technology established at ICIB-CNR. Qubit devices with improved geometry were fabricated with ICIB-CNR's NbN-based technology. Joint experiments were carried out at ICIB-CNR to characterize at liquid helium temperature the Nb qubit devices fabricated by the Hypres foundry. The data acquisition software of the ICIB-CNR was optimized and special MATLAB software for noise analysis was created. The electromagnetic noise of the ICIB-CNR experimental setup was substantially reduced by installation of current dividers and optimized RC low band filters.

[1] R.W. Simmonds, K.M. Lang, D.A. Hite, D.P. Pappas, and J.M. Martinis, *Decoherence in Josephson Phase Qubits from Junction Resonators,* Phys. Rev. Lett. **93**, 077003 (2004)

[2] Jürgen Lisenfeld, *Experiments on Superconducting Josephson Phase Qubits,* PhD Thesis, Universität Erlangen-Nürnberg (2008), ISBN: 978–3–932392–81-8, ISSN : 1617-2574

Firma del Proponente

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