Chapter 8

Applications of superconductivity

Applications of superconductivity are studied in the field of radiation detection at optical and infra-red frequencies and of high-frequency electronics with, possibly, operating frequencies up to 100 GHz. The successful deposition of very high quality NbN thin films showing sharp superconducting transitions at higher critical temperature (16 K) compared to Nb allows the operation of the superconducting elements at higher temperatures and higher frequencies. Other nitride (MoN, NbTiN) and cuprate (YBaCuO, HgReBaCaCuO) superconductors would open the field to even higher operating temperatures and frequencies.

Superconducting devices for radiation detection have the potential to reach single-photon sensitivity using lithographic developments towards sub-micron sized structures. The investigated devices operate as photon detectors using two different mechanisms: the detection of the tunneling current of superconducting tunnel junctions at sub-gap bias-voltages or the detection of the transport current of a hot-electron bolometer close to the superconducting critical current.

Digital logic circuits based on the Josephson effect can reach ultra-high frequencies because of flux quantization where the operating frequencies are determined by the superconducting energy gap (e.g. 500 GHz for a 1 meV energy gap). This so-called Rapid Single Flux Quantum logic is applied for the development of high-frequency analog-digital converters by using arrays of Josephson junctions.
8.1 Superconducting single photon detectors.

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Two kind of superconducting single photon detectors are presently studied in the laboratory: the Superconducting Tunnel Junction (STJ) and the Hot Electron Bolometer (HEB).

The properties of Superconducting Tunnel Junctions make them very suitable for low light level and large photon-energy resolution in astronomical observations such as in ground based infrared and visible interferometer telescopes. Most of this instrumentation is developed in the framework of the Very Large Telescope Interferometer built by the European Southern Observatory in Chile. An example of a 9 pixel array of Ta-STJ detectors operating in the near infrared is shown on Figure 1. The STJ consists of a vertical stack of five layers covering the whole pixel area: the base electrode made of an epitaxially grown tantalum film for photon absorption with an energy gap of about 1 meV, two thin aluminium layers acting as "quasi-particle traps" sandwiching the aluminium oxide tunnel barrier, and a tantalum counter-electrode. Electrical charges created by the impinging photon in the absorber are read-out by voltage biasing the tunnel barrier. The Ta (100) photon-absorber layers are grown epitaxially by DC-magnetron sputtering at 600 °C on the R-plane sapphire substrate in order to get a sufficiently long quasi-particle lifetime (about 10 μs).

The Ta/Al-AlO_x-Al/Ta junctions show a very low sub-gap leakage obscurity current at 0.2 K. The lower energy gap of tantalum in comparison with niobium makes this material better for detecting infrared photons above a 1-μm wavelength. Infrared photon counting has been successfully tested on Ta STJ with an original read-out electronics: very good values of sensitivity and of quantum efficiency have been obtained at 0.2 K while the measured response time is found to be about one microsecond.

The HEB based on very thin nanostructured NbN films are presently intensively studied for both visible or infrared single photon detection as well for low noise THz heterodyne mixers (especially for the ‘HIFI’ instrument of the HERSCHEL Space Telescope to be launched in 2007). A HEB is characterized by a short-lifetime hot spot of quasi-particles nucleated by infrared photons which can be modulated in size and energy at GHz frequencies.

HEB detection requires very thin superconducting NbN layers of good epitaxial quality (about 4 nm thick) grown on suitable substrates heated at about 600°C by DC-magnetron sputtering in a reactive argon-nitrogen plasma. R-plane cut sapphire and (100) oriented MgO are the best substrate choice for the crystalline quality of the NbN layers. Our previous experience on NbN junctions has been applied successfully for obtaining among the very best NbN nano-layer quality as shown on Figs. 2 and 3. The superconducting critical temperature of the layers has been optimized above 10 K with a standard BCS quasi-particle density of states and critical current densities above 10^6 A/cm^2. The main patterning process involves e-beam lithography with a 0.2-μm width of the meander structure as shown in Fig. 4. An attractive alternative route of nano-patterning is achieved in collaboration with CNRS-CRTBT using AFM anodization down to 20-nm lateral and 1-nm vertical dimensions.
Figure 8.3: Temperature dependent critical current of a 3.5 nm thick NbN epitaxial film corresponding to critical current densities above $10^6$ A/cm$^2$ at 4.2 K. Insert: observation of the surface topography of NbN by Scanning Tunnelling Microscopy. The NbN layer shows the replica of the sapphire vicinal steps, 0.4 nm high.

Figure 8.4: View of a photon-detection chip with a coplanar microwave connection. The photosensitive HEB pixel is covered by a meander pattern (lines of 0.2 μm width) achieved by e-beam lithography on a 3.5 nm thick NbN layer. Detailed magnification of the central NbN meander part of the pixel is shown at the right side.

without any detrimental effect on the superconducting film properties. Electrical characterization of our NbN HEBs has been done. Optical photon counting characterization of the NbN HEB is underway in collaboration with UJF-LSP. Our future goal is to compare the figure of merit between STJ and HEB detection in view of the development of a multi-pixel focal plane infrared detector in the field of astrophysics and of an efficient single photon detector in the field of quantum optics.

8.2 Rapid Single Flux Quantum logic circuits

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The Rapid Single Flux Quantum (RSFQ) superconducting logic gates based on Josephson junctions have extremely powerful performances in comparison with semiconducting field effect transistors: a very low thermal dissipation (about $10^{-19}$ J per logic operation) and a very fast transit time of the gates (about 1 ps). This opens the possibility to achieve integrated signal processing circuits operating in the 100 GHz frequency range. Such a frequency range is ten times higher than the projected frequency limit of microprocessor chips in the CMOS road map. Wide bandwidth/high precision analog-to-digital converters (ADC), fast switch networks, Software Defined Radio (SDR), or Tera-flop Desktop Workstations are expected as unique output products for RSFQ chips.

Fast RSFQ technology requires small-sized Josephson junctions with a high current density and superconducting micro-strip transmission lines together integrated in a multilayer circuit. In order to benefit of the high speed of RSFQ, a superconducting Sigma-Delta modulator based on one-bit architecture and operating at 200 GHz is studied as shown schematically on Fig. 5. The design and simulation of the building blocks (stabilized clock, transmission line of logic bits, frequency divider, band-pass filters, couplers,...) of such a modulator have been applied for the NbN system using oversampling of the signals at 200 GHz for a 10 GHz input frequency with an example shown on Fig. 6. Such a fast modulator is the critical part of an analog-to-digital converter with a large bandwidth and high signal carrier frequency (10-30 GHz) in the framework of contracts associating our laboratory to Alcatel Space and CNES for future applications in telecommunication systems.

Today most of the RSFQ circuits are based on superconducting niobium junctions operating at 4 K. RSFQ circuits based on NbN junctions could operate up to 10 K, which represents a gain of a factor 3 or 4 in the cooling requirements and makes them attractive in comparison to niobium circuits for space applications where the cooling system introduces strong weight and dissipation constraints. NbN appears also to be a very good alternative to niobium to reach also higher circuit frequencies due to the higher $T_c$ (16 K) and the larger energy gap of NbN.

A NbN multilayer for RSFQ circuit technology has
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Figure 8.6: Clock frequency generation at 200 GHz, stabilization by a short section of a Josephson transmission line, and frequency division by a factor 2 as simulated for RSFQ based on NbN in a 'T-Flip-Flop' modulator circuit.

Figure 8.7: Current-voltage characteristics of a NbN-Ta$_x$N-NbN Josephson junction including a Ta$_x$N barrier, close to the metal-insulator transition. The self-shunted junction characteristic is well described by the resistively shunted Josephson model.

been developed on 3 inch diameter R-plane sapphire and on silicon substrates. RSFQ circuit technology can take advantage of a high quality NbN buffer layer sputtered epitaxially on the R-Al$_2$O$_3$ at 600 °C. Innovative deposition of a dielectric MgO layer combined with SiO$_2$ deposition improves significantly the superconductivity of NbN junction electrodes deposited up to 300 °C. Good quality 2 µm$^2$ area NbN/MgO/NbN junctions with high J$_c$ (up to 50 kAcm$^{-2}$) are obtained with very large gap voltage (6.20 mV) and low sub-gap leakage current. However, at 4.2 the characteristics are hysteretic. At 11 K, the characteristics of the NbN junctions are found self-shunted without any hysteresis which is the required condition for RSFQ logic cells to achieve very high frequency operations. An alternative for self-shunting the Josephson junctions resides in the development of junctions with a correlated metal barrier such as those based on tantalum deficient Ta$_x$N (see Fig.7 for the current-voltage characteristic). In the cubic phase, Ta$_x$N matches fairly well the NbN crystal lattice of the junction electrodes and is fully compatible with any C-MOS foundry process.

Real ultra-wide band analog-to-digital converters and other ultra-fast logic gate circuits are the target in a 4-year program started in 2004 with the support of the CEA-Leti technological platform. Such an approach has allowed previously to realize in a reliable way, on large area substrates (200 mm diameter silicon wafer), sub-micron sized Josephson junctions with a low area spread compatible with the tolerances of an ADC with 20 000 logic gates on a single chip. First demonstrations, shown on Figs. 8 and 9 are based on TiN electrodes with $T_c$ of 4.7 K only. Planarization techniques have been done successfully by mechanical polishing of SiO$_2$ layers leading to junction line-width down to 0.25 µm in a reliable way. Fortunately a 0.7 µm line-width target is enough to fulfill the technological requirements in the development of NbN RSFQ digital chips clocked at 200 GHz in our project.
Figure 8.9: View of the cross-section of a TiN/Ti$_4$N$_x$O$_y$/TiN Josephson junction laterally planarized with a silica layer developed in collaboration with Leti/Plato for RSFQ circuits.