TOWARDS A QUANTUM CURRENT STANDARD : A SINGLE ELECTRON DEVICE CONNECTED TO A CCC

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The base electrical unit, the ampere, was defined in 1960 and its *realization* was carried out by means of a Pellat-type balance. This experiment was typically difficult, time consuming and the achieved uncertainty was close to 8.10^{-6}. As a result, in practice, the realization of electrical units does not start with ampere of which the representation requires the volt and the ohm. Two discoveries in solid physics, Quantum Hall Effect (QHE, level uncertainty of $\sim10^{-9}$) and Josephson Effect (JE, $\sim10^{-10}$), have revolutionized the electrical metrology in such a way that today they are used in most national metrology institutes for establishing the reference standard of electrical resistance (Ω) and electromotive force (V). These quantum standards are much better than material representations (standard cells or standard resistors) in terms of stability in time, reproducibility and uncertainty.

In the framework of its fundamental electrical metrology activities, the LNE is developing a quantum current standard based on single electron tunneling (SET) effect. A metrological need exists indeed in the fields of very low current and high resistance and a standard current source would provide the missing link of the quantum metrological triangle experiment [1]. Such an experiment is an original way of applying Ohm's law to check out the link between the three electrical quantum standards combined with three quantum effects and two fundamental constants (e, electron charge and h, the Planck constant), the expected uncertainty level being one part in 10^8 as an ultimate goal. This experiment takes place in a more general context : the replacement of the present S.I. by a new international system of physical units based on fundamental constants.

The most promising SET device, the electron pump (Figure 1, left), based on the Coulomb blockade principle, allows the transfer of electrons one by one at an adjustable clock frequency and thus generates a current I directly proportional to electron charge, e, and an applied harmonic signal frequency, f : $I=e.f$. The intermediate electrode between two junctions and a capacitor forms a metallic "island". The capacitance of the fabricated islands is roughly 100 aF involving Coulomb energies equivalent to a temperature of 3-4 K and the measurements are carried out at very low temperatures (30 mK) by using a dilution unit.

Consequently, the Al tunnel junctions surface are close to 50 nm x 50 nm and are fabricated by a standard shadow evaporation technique through a bi-layer mask patterned by e-beam lithography with a JBX5D2U JEOL, in the framework of a collaboration between LNE and CNRS/LPN (Figure 1, right). For the formation of a tunnel barrier, an e-gun evaporator is used. The alumina layer is obtained after deposition of the first layer, the sample is placed during 5 minutes in a chamber with an oxygen pressure kept constant about 5.10^{-3} mbar. The accuracy of the charge transfer is partly limited by co-tunneling. This phenomenon involves simultaneous tunneling of electrons from islands through each junction. In order to avoid errors in the transport rate, on-chip resistive Cr-microstrips of typically 50 kΩ are placed in series at each end of the pump [2], such a device is called R-pump. As a result, dissipation of electron tunneling energy in the resistors suppresses undesirable effects of co-tunneling and thus an increased accuracy can be achieved. Presently, the limit frequencies are roughly 30 MHz and the achieved current intensities are close to 5 pA. In order to measure these very low current with a very high accuracy, LNE has designed a specific amplifier based on a cryogenic current comparator (CCC), which consists of a very sensitive magnetic flux detector (SQUID) combined with a coupling transformer with a large winding ratio. This transformer is made of superconducting wire (NbTi) coils surrounded with a superconducting toroidal shield (Pb). Up today, our CCC is located in Helium bath at 4.2 K and has a gain of 10 000. With an input current noise close to 4 $fA/Hz^{1/2}$ in the white noise region extending down to 0.5 Hz, our CCC-based amplifier allows current measurements from 1 pA to a few fA with a type A uncertainty of 50 aA (1σ) for typically one hour measurement time [3]. As a result, Figure 2 exhibits the I-V characteristics of a R-pump measured at f=10 MHz with our CCC-based amplifier. The relative uncertainty is 2.10^{-4}.

In order to improve our measurement set-up, a new generation of current amplifier has started to be developed, with the collaboration of CNRS/LPN. The windings of this new CCC are made of superconducting Niobium tracks of 1 µm width deposited on a Silicon substrate. This compact device will be able to be directly placed within the dilution unit, in a cell placed at 800 mK, inducing reduced thermal noise. This fabrication technique would allow to build CCC with an expected ultimate gain of 100 000 with a few aA resolution.

References :

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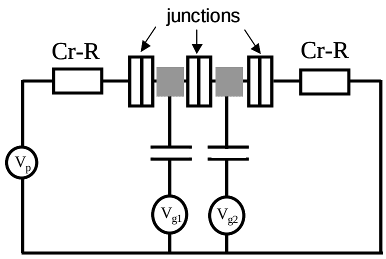
Figures :



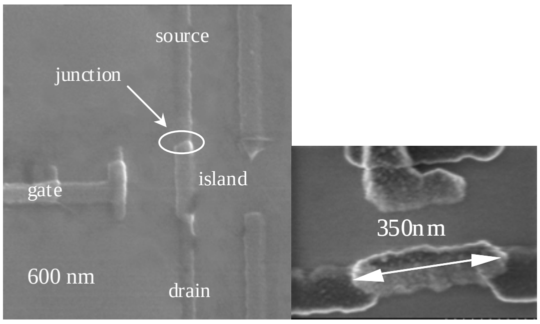


Fig. 1 : On the left, a schematic view of a R-type 3 junctions pump, consisting of a chain of 3 tunnel junctions coupled through capacitors to gate voltages. On the right, a SEM image of a SET device with 2 junctions, with an enlarged picture of an island.

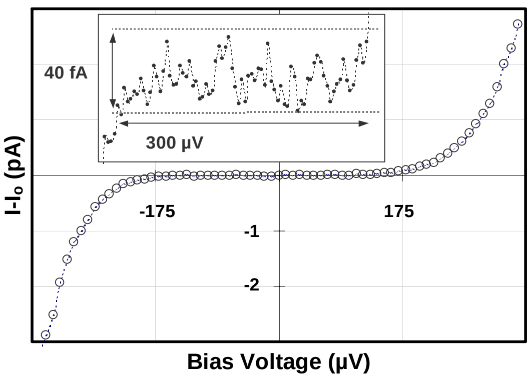


Fig. 2 : Current step measured (*f*=10 MHz) obtained with R-pump provided by PTB (European project COUNT). Y-axis represents current deviation from zero bias voltage current. *IV* curve is fitted by an exponential function taking into account pumping errors. In insert, the plateau of measured current enlarged in the –200 µV/130 µV range.