Josephson Junction Voltage Standard [WIP]

Introduction

In modern metrology as of 20.05.2019, 1 Volt of electromotive force (EMF) is exactly, conceptually defined via the Josephson Constant derived from the Electron Charge *e* and the Planck Constant *h*; $K_J = h/(2e)$ = 483597.84841698... GHz V^1. It was before 01.01.1990's determination of the K_{J90} held as a physical reference standard, an Electrochemical Weston Cell consisiting of a Mercury-Cadmium amalgam, liquid mercury and a saturated water solution of sulfates of both, this was from 1911 the definition of 1.018638V exactly. While highly drift stable and a physical structure and such a true primary standard, not a reference to another standard as all buried zener references of much more common use, the Weston Cells suffered from being a physically embodied standard, being chemical in nature and hence having a significant temperature coefficient, they were also extremely fragile, tipping an unsaturated cell on it's side could cause a cell to become damaged to uselessness and moving one required a settling time of up to months for the cell to stabilize.
The device that phased these cells out was not chemical in nature, not a standalone device that generated a constant voltage, and due to some interesting quantum effects it could generate an

The Josephson effect

The Josephson effect in short summary is caused by two phenomena: Quantum Mechanical tunneling of quasiparticles through a barrier, and superconductivity causing the electrodes on both sides of the barrier each have a single, collective wave function. When a DC voltage V is applied across the sufficiently thin junction, the difference in the phase of the electrode wave functions causes a tunneling of a supercurrent, restoring the imbalance in phase between the electrodes. This will however counteract the voltage imposed on the junction, and as a result an opposite phase imbalance will now exist, causing a new opposing supercurrent and hence a stable oscillation, with a frequency of **exactly** $f=nV*K_J$ where n is an integer. Hence a Josephson junction may be used as a perfect V-F converter. This is the AC Josephson Junction that got Brian David Josephson the 1973 Nobel Prize in Physics, along with Leo Esaki and Ivar Giæver, a Smøregutt (Avsky) from here at NTNU.
If instead an AC current is now applied to the junction, the Josephson current may phase lock to this current and cause a DC voltage to appear across the junction. This voltage will be **exactly** equal to $V=nf/K_J$. A single junction when irradiated by a 75Ghz RF signal will produce voltage steps of only 155uV which is not very much, but the junction is capacitive in nature with virtually no electrode resistance, and so can be designed to pass RF signals with losses of under 0.05dB, hence several hundred junctions can be stringed together. One may also operate the junctions at a higher stable integer n to squeeze more voltage out of each junction by biasing the junction with a dc current and applying more rf power, though this generally also leads to degraded performance.

Physical Structure

In order to make such a set of junctions you need a few things. A substrate to grow the structures on, a superconducting ground plane so the string of junctions can be structured as a microstrip RF transmission line to carry the RF power, a dielectric layer to insulate the junctions, an upper and lower layer of some superconducting material to form the main structure of the standard and in the middle of these two a precise, thin dielectric layer to act as a tunneling barrier. On top of this there may be thicker metallized layers to form pads for easy connections to the outside world, and a passivating final layer of AlOx should be deposited to make the chip more sturdy and oxidation resistant when exposed to air.

A Realistic Structure for manufacturing here at OV

One of the most popular processes to create these structures out of is Niobium (Nb) and Aluminum Oxide (AlOx). Nb is a type-II superconductor and has a critical temperature T_c of 9.2K, is not overly expensive and readily deposited by electron beam physical vapor deposition. AlOx is also easily deposited by an e-beam as long as the proper pyrolytic graphite crucibles are used. It just so happens that our large old Varian 3119 vacuum chamber, Mor Di, has a powerful e-beam system as it's main deposition source. OV does however not currently have setups for photomask spin coating and development as well as etching solutions that can etch Niobium or AlOx effectively, but we'll return to this later.
These chips need to be cooled below their Tc to operate, ideally a fair bit lower to increase stability margins and decrease current noise, this is often done with a dewar full of liquid helium. Liquid helium is a rather expensive consumable, and is not readily available from any sources we have easy access to. What is however very, very handy, is that Mor Di also has a helium Cryocooler built in, working as a cryopump by freezing (ad/absorbing) remaining air to a set of cryopanels coated in a high specific surface area- material (charcoal). This cryocooler, a 2-stage Gifford-McMahon- cooler, is specified to operate down to 8 Kelvin under low gas loads, potentially even lower. While not cold enough to condense helium, it should be more than sufficient for cooling the JJS chip.

This is in many ways what spurred the projects initialization, as many of the hard-to-get parts of such a project all exist inside this magnificent old beast.

More advanced processes use NbN, Niobium Nitride, a Type-II superconductor with a significantly higher T_c at 16K, but must be deposited by reactive sputtering or molecular beam epitaxy (MBE), neither of which we currently have systems for at OV.