## ED3-1-INV

# Single-Flux-Quantum Circuits with Nb-doped Si Barriers


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Digital and mixed-signal rapid single-flux-quantum (RSFQ) superconducting circuits are of significant interest to NIST for metrology applications related to advanced computing, on-chip signal processing, waveform synthesis, and voltage standards (both AC and DC). NIST's development of a high-yielding process for fabricating stacked, self-shunted superconductor/normal metal/superconductor Josephson junctions (SNS JJs) with niobium-doped silicon barriers was critical to productizing the 10V DC programmable Josephson voltage standard.[1] By reducing the Nb doping, we leveraged this process to make high-speed, critically-damped, self-shunted superconductor/*insulator*/superconductor (SIS) JJs for RSFQ circuits operating up to 300 GHz.[2] More recently, we have improved our fabrication process and circuit design and modeling capabilities to build digital RSFQ library cells using a 4 metal layer process incorporating planarization of the insulating layers (Fig. 1). These circuits use SIS JJs with a relatively low 4 K critical current density ($J_c$) of $4.2 \times 10^7$ A/m$^2$ (4.2 kA/cm$^2$); a more advanced process for higher-speed circuits will target SIS junctions with $J_c \sim 10^9$ A/m$^2$ and sub-micrometer diameters defined by electron-beam lithography, as previously demonstrated.[2] To scale our process to more complex high-speed circuits, we moved the ground plane to the top metal layer (M3) and augmented our process control monitor devices and testing to increase yield and ensure accurate parameterization of our Nb-doped Si JJs for operation at both low and high frequencies. As expected, the barrier shunt conductance and the junction capacitance both increase sharply, as the concentration of Nb in the barrier approaches the insulator-to-metal transition. Optimizing these barrier parameters for our circuits is critical to the goal of extending our quantum-accurate waveform synthesizer to RF frequencies.[3]


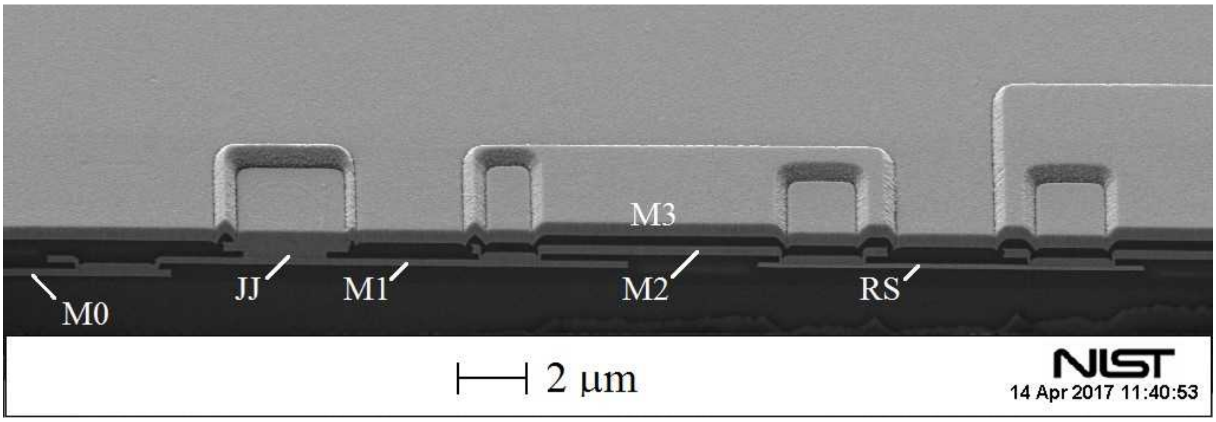


*Fig. 1. FIB-SEM cross-sectional image of a wafer from NIST's 4-metal layer RSFQ process. Josephson junction (JJ), resistor (RS) and Nb metal layers M0-M3 are indicated.*


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2. D. Olaya et al., IEEE Trans. Appl. Supercond., vol. 25, no. 3, pp. 1101505, June 2015.
3. Sam Benz et al., invited talk at ISEC 2017, Sorrento, Italy, June 2017.



Keywords: RSFQ, Josephson junction, metal-insulator transition, superconductive electronics

## ED3-2-INV

### Coherent caloritronics with Josephson circuits: from heat interferometers to 0-π controllable thermal Josephson junctions

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In this talk I will initially report the first experimental realization of a heat interferometer [1-3]. We investigate heat exchange between two normal metal electrodes kept at different temperatures and tunnel-coupled to each other through a thermal device in the form of a DC-SQUID. Heat transport in the system is found to be phase dependent, in agreement with the original prediction. After this initial demonstration, we have extended the concept of heat interferometry to various other devices, implementing the first quantum `*diffractor'* for thermal flux [4, 5], realizing the first *balanced* Josephson heat modulator [6], and an ultra-efficient low-temperature hybrid `*heat current rectifier*' [7, 8], thermal counterpart of the well-known electric diode [9]. The latter structure offers a remarkable heat rectification ratio up to about 140 which allows its implementation in solid-state thermal nanocircuits and general-purpose electronic applications requiring energy harvesting and isolation at the nanoscale. Finally, I will conclude by showing the realization of a fully superconducting heat modulator based on the first tunable „0-π“ *thermal* Josephson junction [10].

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## ED3-3-INV

### Niobium-nitride Based Ferromagnetic Josephson Junctions for Superconducting Qubit Application

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Recently, new research field "superconducting spintronics" appeared, and novel physics and device applications in superconductor/ferromagnet (S/F) hybrid structures have been studied actively. The π state of ferromagnetic Josephson junctions (S/F/S junctions), in which the phase difference between the two superconductors is π in the ground state, is attractive as an intrinsic phase shifter for several superconducting devices based on macroscopic quantum effect [1].

In the present work, we have developed the ferromagnetic Josephson junction in order to realize a superconducting flux quantum bit (qubit) with a π junction [2,3]. The qubit with the π junction can be operated without an external magnetic field which is a noise source, and thus good coherence characteristics is expected. Furthermore, zero magnetic field operation provides merits for realizing a highly-integrated system with many qubits. We adopted niobium nitride (NbN) with high superconducting critical temperature of ~16 K as the superconducting material of the junction, which has a relatively smooth surface due to its epitaxial growth on a magnesium oxide substrate. We used copper nickel (CuNi) for the ferromagnetic barrier as a diluted weak ferromagnet, and fabricated the ferromagnetic Josephson junctions based on NbN electrodes with various junction sizes and CuNi thicknesses. We measured and analyzed the dependences of the Josephson critical current on the temperature and CuNi thickness. As a result, we succeeded to develop NbN-based π junctions, and confirmed that our experimental results were explained well by a microscopic theory of the π junctions [4].

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Keywords: Josephson junction, Superconducting qubit, pi junction, Spintronics

## ED3-4-INV

### Basic Study on AC loss characteristics in frequency band of a few tens of kHz in an HTS pancake-coil for Wireless Power Transmission System

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Due to advances in storage battery technology, application of wireless power transmission (WPT) technology to large-capacity devices such as electric tramways has attracted attention. Generally, as the quality factor $Q$ of the transmission and reception coils is higher, the transmission efficiency of the WPT system becomes higher. Therefore, the high $Q$ is obtained by increasing the operating frequency in a typical WPT system using copper coils. However, it is necessary to lower the operating frequency of the large capacity WPT system due to constraints of the switching frequency of the power converter and the capacity of the power supply. Therefore, when copper coils are used for WPT system in a few kHz frequency band, it is difficult to achieve both high capacity and high efficiency.

We are investigating the possibility of large capacity wireless power transmission system with high temperature superconducting (HTS) coils in frequency band of a few tens of kHz. HTS conductor does not have electric resistance. However, when an alternating current flows through an HTS conductor, an AC loss occurs. An equivalent resistance of an HTS coil is obtained by dividing the AC loss of the coil by the square of RMS value of the AC current and the transmission efficiency of the WPT system largely depends on the equivalent resistance of the HTS coil. Fig.1 shows measurement results of the AC loss and the $Q$ of an HTS coil wound 10 turns by an HTS coated conductor with a copper layer. In the copper coil, the $Q$ increases almost in proportion to the frequency. On the other hand, in the superconducting coil, the frequency increases, the $Q$ decreases. This is because the eddy current loss per second in the copper layer increases with the square of the frequency. In the HTS coil, the $Q$ decreases much as the exciting current increases, but the $Q$ is higher than that of the copper coils at 10kHz or less. More experimental results and analyses will be presented in detail.

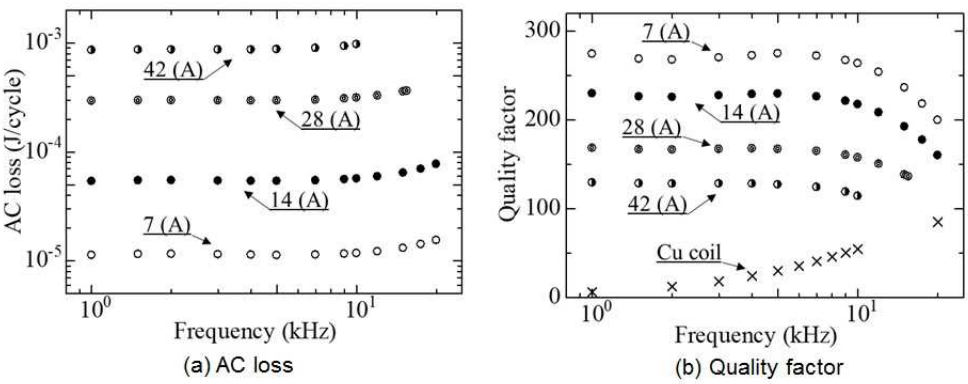


Fig.1 Measurement results of AC losses and quality factor $Q$ in the HTS and Cu coils as a function of frequency.

## ED3-5

# Generation of Circularly Polarized THz Radiation from $Bi_2Sr_2CaCu_2O_{8+\delta}$ Mesa Structures

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In the last decade, continuous wave terahertz sources based on high-$T_c$ superconducting $Bi_2Sr_2CaCu_2O_{8+d}$ (Bi2212) were extensively studied [1]. Mesa-shaped Bi2212 THz sources are compact in size, has a broad tunability range, and extremely monochromic radiation. In many applications, polarization control of the THz radiation is required. However, commonly studied Bi2212 sources in the shape of a rectangular mesa are linearly polarized [2]. Circular polarization (CP) is achievable in Lab environments by using external optical devices such as quarter wave plates. Nevertheless, monolithic generation of CP is highly in demand for compact and portable devices.
In previous reports [3, 4], the CP THz emission from Bi2212 sources has been numerically studied. In the present study, we experimentally show a monolithic Bi2212 based source capable of generating CP THz radiation. The device discussed in this study is in the shape of a cylindrical mesa with two notches, one on each side of its diameter. In a temperature of 30 K, the polarization state, as represented by the axial ratio (AR), was found to be as low as 0.5 dB with a tunability between circular to elliptical polarization (> 3dB). The polarization properties are measured by using a rotating wire-grid polarizer in the emission path between the source and a Si-Bolometer.

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Keywords: Intrinsic Josephson Junctions, Terahertz, Polarization