Superconducting SIS Mixers with Vertically Stacked Junctions

Ming-Jye Wang, Tse-Jun Chen, Chuang-Ping Chiu, Wei-Chun Lu, Jing Li, and Sheng-Cai Shi

***Abstract*—The SIS mixers with two vertically stacked junctions, VSJ, have been fabricated. Using standard Nb-technology, the Nb/Al-AlOx/Nb/Al-AlOx/Nb multilayer is deposited in a single vacuum process. The junction, near 1μm^2 in size, is defined by etching the top three layers (Nb/Al-AlOx/Nb) using ICP-RIE system. The receiver noise of mixers are measured in the 4K wet dewar. Wide bandwidth is demonstrated in VSJ mixers, which is consistent with the Fourier Transformation Spectroscopy, FTS, results. The numerical simulations demonstrate a similar behavior as experimental result, but shift to lower frequency. This discrepancy might result from some difference between the model and real device (mixer mount in particular).**

***Index Terms*—Fourier Transform Spectroscopy, receiver noise temperature, superconductor-insulator-superconductor mixers.**

I. INTRODUCTION

VERTICALLY stacked SIS junction (VSJ), with individual junctions connected in series but without introducing any additional connection wires, has been demonstrated as mixer operated at frequency above 100GHz [1-3]. The advantages of mixer with junctions in series are having a simple structure and an equivalent normal-state resistance of relatively large value, which makes impedance matching easier in mixer application. In addition, the dynamic range of VSJ mixer can improved by a factor of N^2 [4, 5], where N is the number of series SIS junctions. The design of junction in series could also improve the gain compression problem, especially in low frequency range. Furthermore, the photon-assisted quasi-particle tunneling in the stacked SIS junction becomes interesting if the thickness of middle Nb is rather thin. The tunneled quasi-particle might not re-condense to superconducting pairs in the middle layer of Nb before the second tunneling happened. Non-equilibrium phenomena might become important and modified the mixing result. Recently, THz radiation had been demonstrated in high temperature superconductor which has intrinsic stacked Josephson junctions [6]. However, the challenge is to fabricate junctions with identical parameters. For conventional type, the individual tunnel junction is fabricate at same growth condition and is connected with the adjacent junction by a Nb film. In this type, the superconducting critical current density, J_c, of junction should have good uniformity. However, the size of junction is dependent on the quality of photo-lithography process, especially for small junction. On the other hand, the VSJ type is easy to have identical junction size because of using the same PR pattern, but having same critical current density in both junctions might be the critical issue. In this paper, we would like to report the fabrication of VSJ mixers and their DC/RF characteristic results. A numerical simulation program based on quantum mixing theory with five ports model was performed to simulate the mixer performance.

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II. DEVICE FABRICATION

The VSJ mixers are fabricated by conventional Nb-AlOx-Nb junction technology [7]. Two stacked junctions with structure of Nb/Al-AlOx/Nb/Al-AlOx/Nb are grown in situ without breaking the chamber vacuum. The fabricating procedures are shown in Figure 1. The thickness of middle Nb is 100nm to avoid the complication in simulation model. As mentioned above, the J_c and size of junctions are two important issues for VSJ mixer fabrication. Firstly, the tunneling barriers of two junctions should have same J_c. According to our previous study [8], the value of J_c is very sensitive to the wafer temperature. Therefore, during the growth procedure, wafers were well thermally anchored to a temperature control cooling stage. Another important issue is to keep the sizes of two stacked junctions same. Low processing pressure was performed to etch the Nb/Al-Ox/Nb trilayer in our ICP-RIE etching system. Designs for 400GHz frequency band mixers with regular single junction are used in the experiment. Therefore, the impedance matching was not optimized for reported VSJ mixers.

III. RESULTS AND DISCUSSIONS

A. DC characteristics

The DC I-V characteristics with various external magnetic fields are shown in the Figure 2. The supercurrent of junction can be suppressed by adjusting the external magnetic field. The inset shows the magnetic dependence of junction current biased at voltage of 0.1mV. A Fraunhofer-pattern-like magnetic field dependence of supercurrent was observed. The I-V curves with magnetic fields at different current minimum in I-B curve were also illustrated in the Figure 2. As the magnetic field increased, the gap structure is smoothened due the suppression of superconducting proximity effect in Al layer near the tunnel barrier. All features of DC I-V characteristic show that our VSJ mixer behaves just like a mixer with single junction, indicating that these two stacked junctions have identical parameters. This result will simplify the simulation model during data analysis.

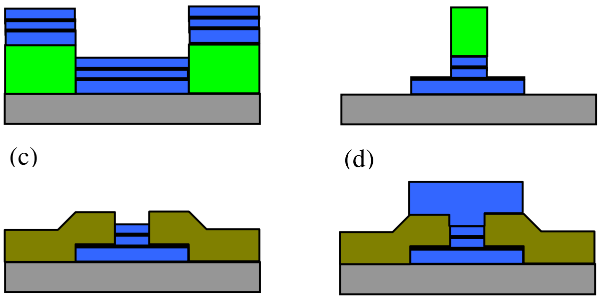

Fig. 1. The fabricating process of VSJ mixers. (a) The growth of double tunneling barrier structure, Nb/Al-AlOx/Nb/Al-AlOx/Nb. The respective thickness of base, middle, and top Nb is 200nm, 100nm, and 100nm. (b) The junction patterning by ICP-RIE system. SF_6 and Ar processing gases were used for Nb and Ar etching respectively. (c) 300nm thick SiO_2 deposition and lift-off. (d) The wiring Nb deposition (500nm).

B. *Fourier Transform Spectroscopy Measurement*

The Fourier transformation spectroscopy technique is an excellent tool to evaluate the RF response of a detector. VSJ mixer was mounted in a 400GHz mixer block designed for SMA receiver. The mixer block, then, was mounted on the cold plate of liquid helium dewar with optical window. The room temperature window was made of 23 µm thick mylar film. Two Zitex films were mounted at 77K and 4K stages respectively, in front of mixer block, to block the IR radiation. The VSJ mixers were biased at 4mV by a battery-based bias circuit. Our FTS system is model of FARIS-1, made by JASCO, Japan. The system has a light source with an equivalent black body temperature of 5000K. The scanning speed of movable roof mirror is set at 0.5mm/sec. The final output signal of VSJ mixer is averaged from 50 scan results. The transformed spectrum has a frequency resolution of 3.5GHz.

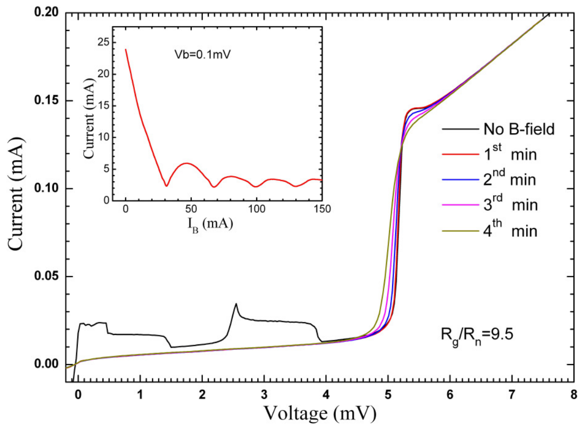

Fig. 2. The DC IV characteristics of VSJ mixer with external magnetic field. The inset shows the magnetic field dependence of supercurrent. The VSJ behaves just like a regular SIS tunneling junction.

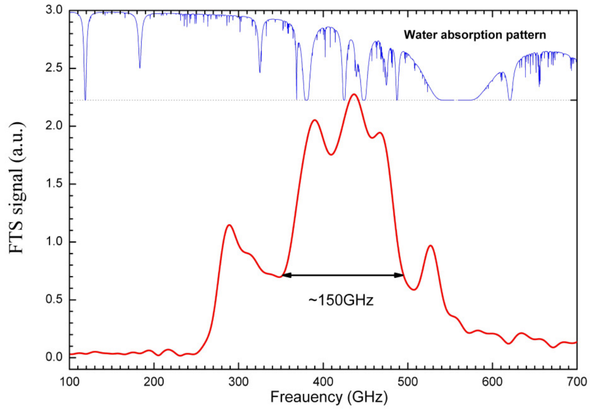

Fig. 3. The RF response of VSJ 400GHz mixer measured by Fourier transform spectroscopy system. Two strong suppressions near 330GHz and 500GHz are observed. The upper part of figure shows the absorption spectrum of water. The bandwidth of VSJ 400GHz mixer is more than 150GHz, and even can be expanded to 220GHz if the degradation near 330GHz can be improved.

The FTS response of VSJ 400GHz mixer are shown in Figure 3. A broad band response was observed from 270GHz to 540GHz. The lower frequency response is limited by the cut-off frequency of wave guide, 636µm×158µm. The upper frequency is limited by the tuning circuit of mixer chip. Two strong dips were observed near 330GHz and 500GHz. According to the water absorption spectrum, as shown in the upper part of Figure 2, the absorption lines are not coincident with the dip structure of FTS result. Therefore, we can exclude the absorption of water condensed on the window. We will discuss this issue later. The VSJ mixers can have a bandwidth larger than 150GHz if we defined the FWHM (full width at half maximum) as the bandwidth of RF response of a detector. The bandwidth can be even expanded to 220GHz if the degradation near 330GHz can be improved.

C. *Receiver Noise Measurement*

The VSJ 400GHz mixers were tested by typical hot/cold load method. The magnetic field is set at the 3rd minimum of I-B curve to suppress the superconducting pair tunneling. The RF and LO signals were coupled by a wire grid with a proper angle relative to the waveguide of mixer block to have enough LO pumping. The contribution from the loss of RF/LO coupler has been subtracted by standard procedures. The signal coupling efficiency was calculated by projecting the wire gird angle to waveguide plan. Then the corrected T_{rx} is obtained through the formula of $T_{rx} = T_{rx}' \times C - T_{amb} \times (1 - C)$, where T_{rx}' is the uncorrected receiver noise temperature, C is the coupling efficiency of wire grid, T_{amb} is the ambient temperature. Two sets of LO source were used to cover wide frequency range (240GHz~500GHz).

Figure 4 shows a typical I-V and P_{IF}-V curves of VSJ mixer under optimum LO pumping. The nominal LO frequency is 288GHz. Very similar to a regular mixer, photon-assisted quasi-particle tunneling steps were observed clearly, except of doubling the voltage value. The doubled photon-assisted

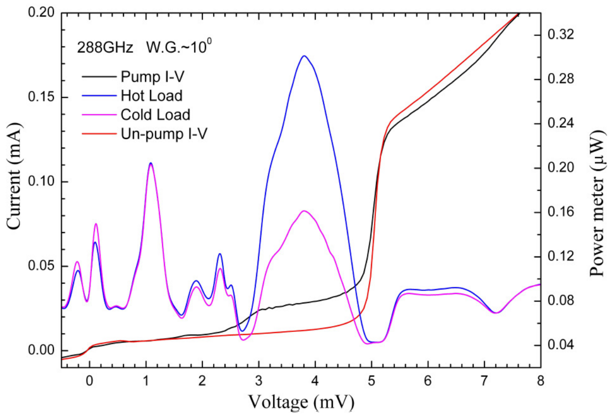

Fig. 4. The I-V and PIF-V curves of VSJ mixer with optimum LO pumping. The photon-assisted quasi-particle tunneling steps are observed clearly.

quasi-particle voltage steps provide the advantages of avoiding the gain compression effect and having a wider range of the optimum bias point.

The corrected receiver noise temperature, T_{rx}, of VSJ mixer was illustrated in the Figure 5, accompanying with the FTS result for comparison. The overall frequency dependence of T_{rx} is consistent with the FTS spectrum. T_{rx} becomes higher at the frequency with low FTS response. The value of T_{rx} of this VSJ mixer is about 150K in a wide frequency range of 270GHz to 480GHz, except of being a higher value of 250K near 340GHz. The receiver noise temperature is higher than that of the regular mixer designed for Taiwan receiver of SMA, ~80K. We attribute this difference to the RF mis-matching because the tuning structure of these VSJ mixers is identical to the regular mixers.

D. Numerical Simulation

On the numerical simulation, we treated a VSJ just like conventional junction arrays in series, with its equivalent normal-state resistance (i.e., measured R_n for the VSJ) twice that of individual junctions and its equivalent geometric capacitance half that of individual junctions. The voltage and current of its dc I-V curve was both reduced by a factor of two for simulation [9]. With the measured R_n (34Ω) and calibrated junction critical current density J_c (~10kA/cm^2), the junction area was estimated to be slightly larger than 1μm^2 in terms of the constant I_cR_n product, which was assumed to be 1.95mV. Thus the equivalent geometric capacitance was equal to 52fF by taking a specific capacitance of 90fF/ μm^2.

The mixing behavior of the measured VSJ was simulated by using the quantum theory of mixing [9] with a quasi-five port model [10]. The RF embedding impedance seen by the VSJ was obtained with the help of HFSS simulation and modeling for thin-film superconducting microstrip lines as integrated impedance transformers and tuning inductance, while the IF impedance was simply taken as 50Ω. During simulation, the dc bias voltage (as for a single junction) and reduced LO pumping level were both optimized for the receiver noise temperature at each frequency.

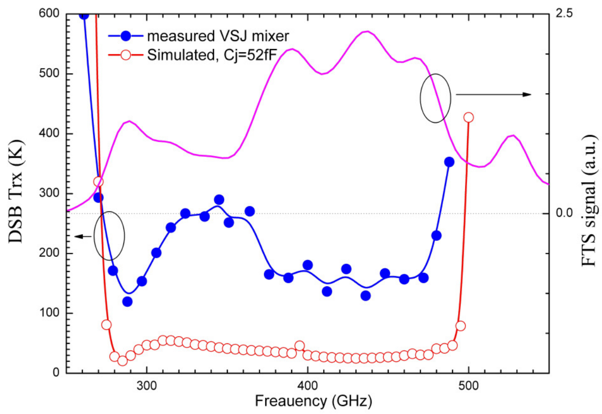

Fig. 5. The corrected receiver noise temperature of VSJ mixer, solid circles. The simulated mixer performance is also shown, open circles. The simulation result has similar feature as the experimental data, except of shifting the bump to lower frequency.

The simulated receiver noise temperature was shown in Figure 5, open circles. The simulated data has a bump, similar to experimental results but shifted to a lower frequency of 320GHz. It might be due to the discrepancy between model and real devices and also mixer block. However, the overall measured receiver noise temperature is much higher than the simulated result. Detailed breakdown of receiver noise sources is necessary to understand the reason of this large difference.

IV. CONCLUSION

We have fabricated 400GHz mixer with vertical stacked junction (VSJ) by using Nb-based technology. The VSJ behaves like a single barrier SIS junction, indicating the stacked two junctions have identical size and J_C. The FTS spectrum and receiver noise temperature demonstrate the VSJ mixer has a bandwidth larger than 110GHz, although the on chip tuning circuit is not designed for it. The VJS mixer has worse performance around 340GHz which might be attributed to large impedance mismatch. A numerical simulation was done to model the equivalent circuit of the stacked junctions. We have demonstrated the good consistency between measurement and simulation results. However, the receiver noise temperature is still much higher than the simulation result. Further works are needed to understand the reason of this difference.

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