Fabrication of all-NbN digital-to-analog converters for programmable voltage standard

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Abstract – **Five bit all-NbN digital-to-analog converters (DACs) for a programmable voltage standard have been fabricated using NbN/TiN/NbN Josephson junctions and their operation has been demonstrated. The DAC consists of arrays of 128, 128, 256, 512, 1024 and 2048 junctions. We have measured current-voltage characteristics for the junction arrays driven with a 16 GHz microwave signal at 4.2 K and 10 K, resulting in Shapiro steps with amplitudes larger than 2 mA. The maximum output voltage for the DAC was 136 mV, indicating that all 4096 junctions in the DAC yielded a voltage corresponding to the microwave frequency.**

I. Introduction

A number of DACs for programmable Josephson voltage standards have been developed by several groups [1]–[3]. Burroughs *et al.* demonstrated a programmable 1 V Josephson voltage standard system using 32768 Nb/PdAu/Nb junctions driven at 16 GHz which resulted in $\pm$ 33 μV constant voltage steps for each junction. [4]. Schulze *et al.* reported the fabrication of junction arrays for a programmable 10 V voltage standard system, which used 69120 Nb/AlOx/Al/AlOx/Nb junctions [5].

We have been developing DACs for the programmable Josephson voltage standard using NbN/TiN/NbN junctions. The use of NbN/TiN/NbN junctions has been motivated by the high T_c ($\geq$ 16 K) in NbN electrodes and by good controllability of I_cR_n and J_c. The former allows us to operate DACs at a temperature near 10 K with a compact closed-cycle refrigerator. The latter ensures a high fabrication yield. In previous papers [7], [8], we reported the fabrication of NbN/TiN/NbN junctions on Si wafers, and the uniformity of electrical characteristics of fabricated junctions. In this paper, we report the fabrication of 5 bit DACs and their characteristics.

II. Experiments

Photomasks using the same 16 GHz microwave design as in [4], [6] were designed and fabricated at NIST. The fabrication process of our NbN DAC is as follows. First,

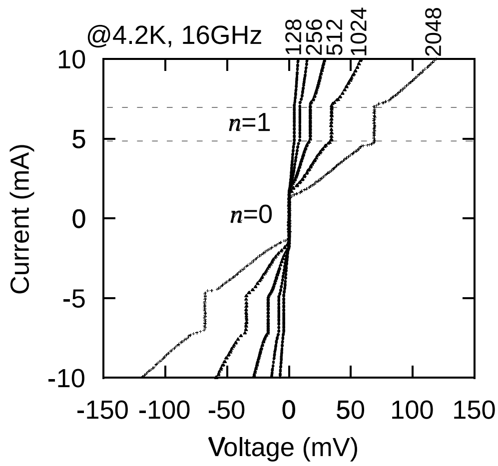

Fig. 1. I–V characteristics of 128, 256, 512, 1024 and 2048 junctions at 4.2 K. The microwave drive frequency is 16 GHz. The n=1 steps have amplitudes greater than 2 mA. The maximum voltage when all arrays are biased simultaneously is 136 mV.

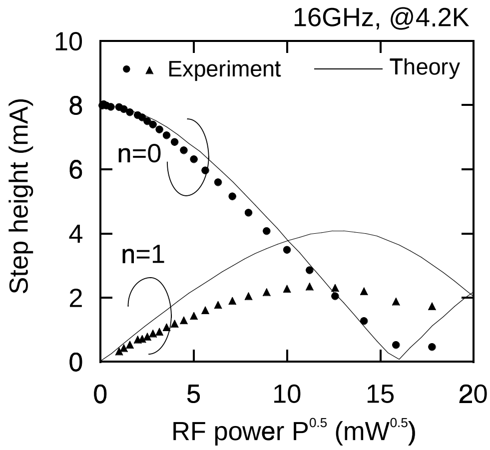

Fig. 2. Dependence of the step current range on the rf power. The number of junction is 128. Closed circles and triangles show the dependence of the current range (n=0 and n=1) on the rf power. Lines show theoretical predictions.

a NbN film of 300 nm was deposited by reactive rf sputtering on a Si wafer. After patterning the NbN film by dry etching, a NbN/TiN/NbN junction was prepared by reactive rf sputtering. The typical thickness of both the base and counter NbN films was 100 nm. The thickness of the TiN barrier was either 50 nm or 25 nm. The former thickness was chosen to have an $I_c R_n$ value of about 30 μV at 4.2 K and the latter at 10 K [8].

Before fabricating all-NbN DACs, we fabricated a number of DACs using 300 nm thick SiO_2 followed by 800 nm thick Nb wiring. The electrical characteristics of the DACs with Nb wiring were measured at 4.2 K. Using the same fabrication process for all-NbN DACs, we found that the critical current for NbN wiring was much smaller (10 – 20 mA) than the 100 mA critical current for Nb wiring. The reduced I_c for NbN wiring may be due to defects in the wiring at the base electrode cross overs or at insulator cross overs near the junctions. To improve the I_c for NbN wirings, we introduced a chemical mechanical polishing technology into the fabrication process. As a result, we succeeded in achieving > 50 mA critical current for NbN wiring.

Figure 1 shows I–V characteristics of a 5-bit DAC at 4.2 K. The DAC has series arrays of 128, 128, 256, 512, 1024 and 2048 junctions and the total number of junctions is 4096. The critical current for junctions was about 4 mA. For a 16 GHz microwave drive frequency the arrays achieved constant voltage n=1 steps while amlitude greater than 2 mA. The total voltage for the entire array reached 136 mV, indicating that all junctions in the DAC yielded a voltage corresponding to the microwave frequency of 16 GHz. Constant voltage Shapiro steps were also observed for all 5 bits of this all-NbN DAC at 10 K.

Figure 2 shows the dependence of the step height on the square root of the rf power for the smaller array. The number of junctions was 128 and the temperature was 4.2 K. The amplitude of the rf power was monitored at the output of a microwave source. The actual rf power coupled to the junction arrays could be much smaller than that in Fig. due to losses in coaxial cables, impedance mismatching, etc. The closed circles and triangles show measured step heights for n=0 and n=1, respectively. Lines represent theoretical predictions calculated using the resistively shunted junction model. Although the n=1 step current is smaller than theoretically expected, its 2 mA amplitude is large enough for the operation of a DAC. When an 8 GHz signal was applied, good agreement was obtained between the measured step heights and the calculated ones. For Nb/Pd-Au/Nb junction arrays, it was also reported that the experimental step heights appeared lower than the calculated ones at high frequencies and high step numbers due to junction and microwave power non-uniformity [9].

Figure 3 shows the operation of 4 bit and 5 bit DACs at 4.2 K. Independent bias currents of about 6 mA were supplied to each array in Fig.1. The highest output voltage was about 136 mV.

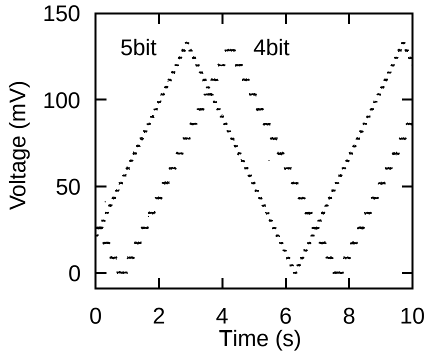

Fig. 3. Operation of 5 bit and 4 bit DACs fabricated with NbN/TiN/NbN junctions.

III. Summary

Operation of DACs using NbN/TiN/NbN Josephson junctions for a programmable voltage standard has been demonstrated. Output voltage of 136 mV was obtained for 4096 junctions driven with a 16 GHz microwave signal. The current range of the 1st step was greater than 2 mA. This step amplitude is large enough to operate the DACs as a programmable voltage standard.

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