

All-NbN digital-to-analog converters for a 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_x/NbN Josephson junctions and their operation has been demonstrated. The DAC consists of six arrays of 128, 128, 256, 512, 1024 and 2048 junctions per array. We have measured the current–voltage characteristics for the junction arrays driven with a 16 GHz microwave signal at 4.2 and 10 K, resulting in constant-voltage steps with heights larger than 2 mV. 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 through the ac Josephson effect.

1. Introduction

A number of DACs using superconductor/normal metal/superconductor (SNS) Josephson junctions for programmable Josephson voltage standards have been developed by several groups [1–3]. An SNS Josephson junction is desirable for DACs because it does not have hysteresis in the current–voltage characteristics; this enables fast switching to obtain arbitrary waveforms. The high critical-current density J_c of the SNS junctions also makes it possible to obtain large output currents. Burroughs *et al* demonstrated a programmable 1 V Josephson voltage-standard system using 32 768 Nb/PdAu/Nb junctions driven at 16 GHz resulting in $\pm 33 \mu\text{V}$ 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/AIO_x/Al/AIO_x/Nb junctions [5].

We have been developing DACs for the programmable Josephson voltage standard using NbN/TiN_x/NbN junctions. The use of the NbN/TiN_x/NbN junctions has been motivated by the high T_c (≥ 16 K) in NbN electrodes and by good controllability of $I_c R_n$ and J_c , where I_c , R_n and J_c are the critical current, the normal resistance and the critical-current density for the junction, respectively. The former will allow 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 [6–9], we reported the fabrication of NbN/TiN_x/NbN junctions on Si wafers and the uniformity of the electrical characteristics of fabricated junctions. In this paper, we report the fabrication of 5 bit DACs and their operation at 10 K.

2. Experimental details

Photomasks using the same 16 GHz microwave design as in [4, 10] were designed and fabricated at NIST. Using the photomasks, the DAC circuits were fabricated at the National Institute of Advanced Industrial Science and Technology (AIST). A cross-sectional view of a DAC circuit is illustrated in figure 1. First, a NbN film of 320 nm was deposited by reactive rf sputtering on a Si wafer which was covered with a 16 nm thick MgO film. The MgO film functions as an etch stop for the patterning of the NbN film. The thickness of the NbN film was chosen to be larger than the 280 nm penetration depth of the NbN film [11]. After patterning the NbN film by reactive ion etching, an SiO₂ film of 400 nm was deposited by rf sputtering. Planarization of this layer was carried out with a chemical–mechanical polishing (CMP) system [11]. This planarization process is important in order to avoid significant reduction of wiring critical currents due to defects at step edges. A NbN/TiN_x/NbN trilayer was

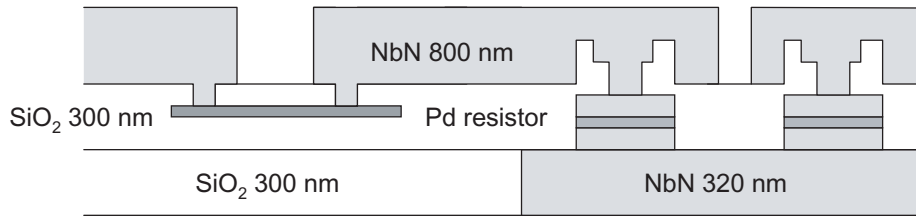


Figure 1. A cross-sectional diagram showing the fabrication process of two series SNS junctions and a termination resistor.

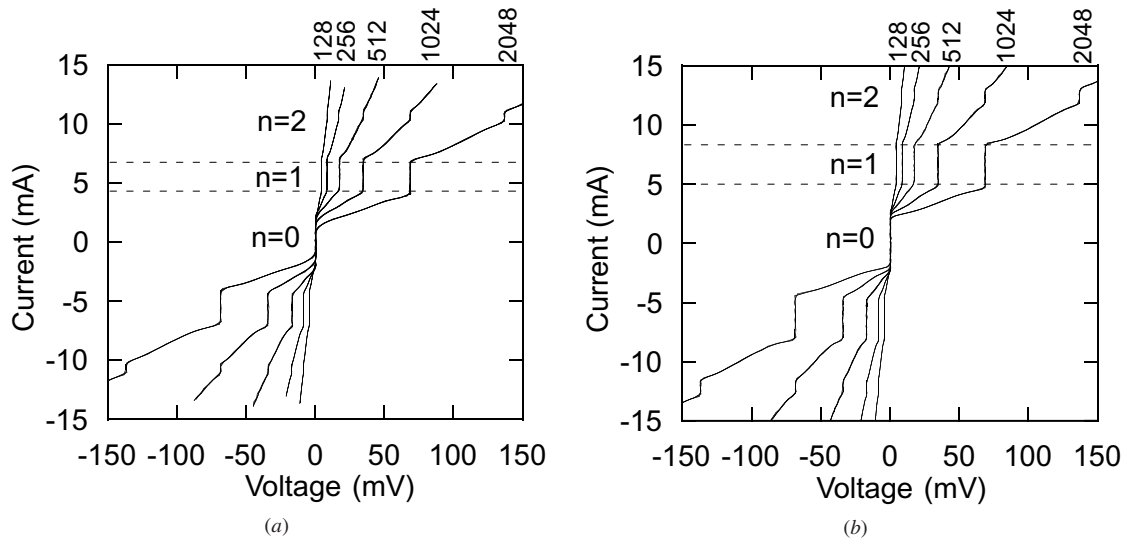


Figure 2. I - V characteristics of 128-, 256-, 512-, 1024- and 2048-junction arrays at (a) 4.2 K and (b) 10 K with a 16 GHz microwave drive. The microwave power was adjusted to maximize the $n = 1$ constant-voltage step.

deposited on the planarized surface of the wafer by reactive rf sputtering. The typical thickness of both the NbN base and counter electrodes was 100 nm. The thickness of the TiN_x barrier was either 35 nm or 20 nm which is chosen in order to have an $I_c R_n$ value of about $30 \mu\text{V}$ at 4.2 and 10 K, respectively.

These thickness values are different from those (50 and 25 nm) reported previously [9]. Thinner barriers for the latest circuits are necessary because a new Nb sputtering target caused a decrease in the critical current density and the $I_c R_n$ product for the junctions with the same TiN_x thickness used for the previous Nb target. At present, the origin of this effect is not known.

We used a sputter-deposited 50 nm Pd film for termination resistors in the microwave circuits. The patterning of the Pd films was carried out using a lift-off method. By controlling the thickness of the Pd resistors, a designed resistor value of $50 \pm 5 \Omega$ was reproducibly obtained.

A total of 300 nm of rf-sputtered SiO_2 insulating film was deposited above the trilayer and resistor layer via holes which were reactively ion etched down to the resistors and counter electrodes. Finally, an 800 nm thick NbN film was deposited and patterned by reactive ion etching for wiring between the counter electrodes of the junctions.

3. Results and discussion

The DAC chips were cooled at 4.2 or 10 K using a liquid He dewar. The temperature of the chip was measured using

a calibrated Ge resistor in thermal contact with the chip. Current-voltage (I - V) characteristics for all junction arrays in DAC chips were measured with and without microwave power. Figure 2(a) shows the I - V characteristics measured for five arrays in a 5-bit DAC chip at 4.2 K with microwave power. The TiN_x barrier thickness for this chip was 35 nm. The junction arrays were composed of independently biased 128, 128, 256, 512, 1024 and 2048 junctions for a total of 4096 series-connected junctions. Figure 2(b) shows the I - V characteristics measured for junction arrays in another 5-bit DAC chip at 10 K with microwave power. This chip had a TiN_x barrier thickness of 20 nm needed for operation at 10 K. The critical current without microwave power for the junctions in both the DACs in figure 2 was about 5 mA.

With a properly tuned microwave signal at 16 GHz, the arrays in the 4.2 K DAC showed constant-voltage steps with a height, or current range, of over 2 mA for the $n = 1$ step. The arrays in the 10 K DAC had step heights greater than 3 mA for the $n = 1$ step. The total output voltage for both the DACs reached 136 mV indicating that all junctions in the DACs yielded a voltage corresponding to the ac Josephson effect. However, the uncertainty in the output voltage remains to be measured using a conventional voltage standard system.

Figures 3(a) and 3(b) show the dependence of constant-voltage step heights on the square root of the microwave power for a 128-junction array at 10 K. The frequency of the microwave signal was 8 GHz for figure 3(a) and 16 GHz for figure 3(b). The power was monitored at the output of

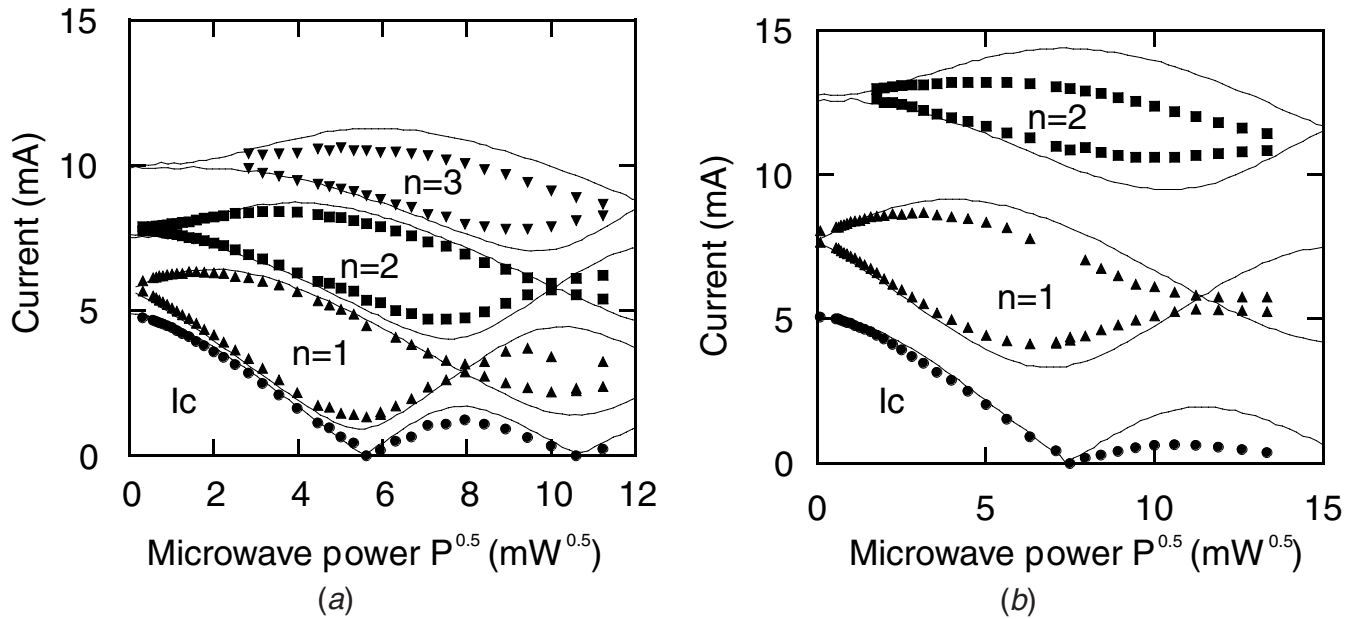


Figure 3. Dependence of the constant-voltage step heights on the microwave power for a 128-junction array at 10 K. The frequency of the applied microwave is (a) 8 GHz and (b) 16 GHz. Closed circles, triangles, squares and reversed triangles show the dependence of the current range ($n = 0, 1, 2$ and 3) on the power. Solid curves show theoretical predictions.

a microwave source. The actual microwave power coupled to the arrays could be much smaller than that in the figures, due to losses in co-axial cables, impedance mismatches, etc. The closed circles indicate the measured zero-voltage critical currents. The closed triangles, squares and reversed triangles show the minimum and maximum measured step heights for $n = 1, 2$ and 3, respectively. The curves represent theoretical predictions calculated using the resistively shunted junction (RSJ) model for a single junction. The x -axis for the calculated results was adjusted to the measured data by fitting the first zero of the critical current to the measured data.

As seen in figure 3(a), if an 8 GHz signal was applied, good agreement was obtained between the measured step heights and the calculated ones, at least at low power. In contrast, if a 16 GHz signal was applied, there was a significant difference between the measured data and the calculated current for all power values. From figure 3(b), it is also clear that the difference between the measured data and the calculation increased with step number. These increasing differences between measured and calculated step heights with increasing microwave frequency, power and step number were also observed for DACs fabricated using Nb/PdAu/Nb junctions [12]. For the PdAu barrier junctions the differences were attributed to both junction and microwave power non-uniformity along the arrays.

Figure 4 compares the measured microwave power dependence of critical currents and constant-voltage step heights for the largest (2048-junction) and smallest (128-junction) arrays at a microwave frequency of 16 GHz. The solid curves show the critical current and step heights for the 2048-junction array at 10 K. The dashed curves show the critical current and step heights for the 128-junction array. In figure 4, we find little difference between the experimentally measured data for the two different size arrays. The microwave power variation of the critical current and step heights for the 256-, 512- and 1024-junction arrays are very similar to the

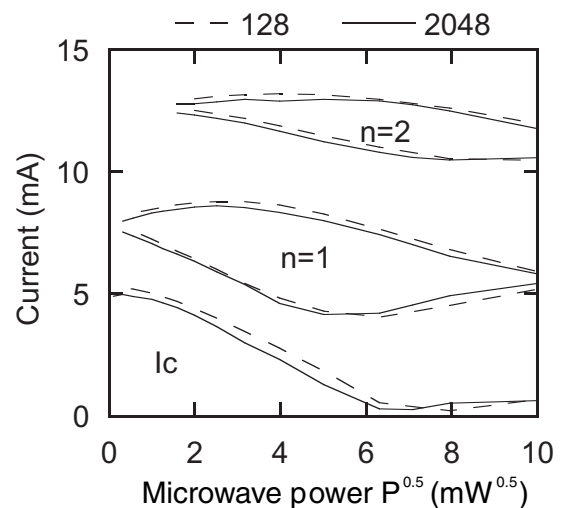


Figure 4. Microwave power dependence of the step current height comparing arrays with different numbers of junctions at 10 K. Dashed and solid curves show the data for a 128-junction array and a 2048-junction array, respectively.

data shown in figure 4. These results indicate that the junctions integrated on a chip have uniform electrical characteristics and also that microwave power dissipation in the arrays is very small. However, the dissipation in 2048 junctions is smaller than that expected for the SNS arrays. We also observed small hysteresis in the I - V curves. These results suggest the existence of capacitance in the junction. It is possible that a very thin insulating layer (possibly, a Schottky barrier) existed between the NbN and TiN_x layers and that the resistance of the TiN_x layers was small compared to the tunnelling resistance of the SIN structure. If this assumption is true, the hysteresis in the dc array I - V curve for junctions and the small microwave power dissipation in the series arrays can be explained.

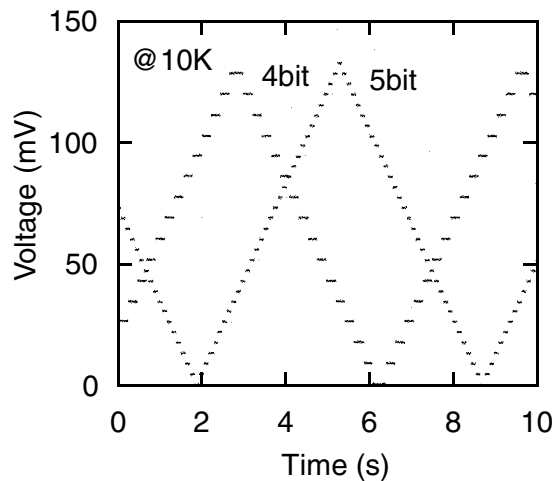


Figure 5. 10 K operation of 5-bit and 4-bit DACs fabricated with NbN/TiN_x/NbN junctions.

Figure 5 shows the operation of the 4-bit and 5-bit DACs at 10 K with a 16 GHz microwave drive. The total number of junctions is 4096 and the highest output voltage is 136 mV. Bias currents of about 6 mA were independently supplied to each of the junction arrays in the DAC. The switching of the bias currents was performed with mechanical relay switches. At present, the speed of the converter operation is limited by the performance of the relay switches.

4. Conclusions

Digital-to-analog converters for a programmable voltage standard have been fabricated using the NbN/TiN_x/NbN Josephson junctions and their operation has been demonstrated at 4.2 and 10 K. The results of microwave power dependence measurements of constant-voltage step heights for junction

arrays integrated on a chip show that the junctions have high uniformity and that the microwave power dissipation in the arrays is small. Furthermore, we have experimentally shown that constant-voltage step heights over 3 mV can be obtained for junction arrays with a microwave drive at 10 K. These results encourage development of all-NbN DACs for a liquid-He-free programmable voltage standard system.

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