NbN-BASED DIGITAL-TO-ANALOG CONVERTERS FOR A PROGRAMMABLE JOSEPHSON VOLTAGE STANDARD

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Abstract

Two kinds of digital-to-analog converters (DACs) for a programmable Josephson voltage standard have been fabricated using NbN/TiN/NbN junctions. One is 8-bit DACs containing 32 768 junctions each. The other is 11-bit DACs containing 327 680 junctions each. The former has ability of generating 1 V-output voltages and the latter 10 V-output voltages. Both devices have been operated with a compact cryocooler.

Introduction

A digital-to-analog converter (DAC) consisting of Josephson junction arrays and a microwave-distribution circuit is used as a key device for a programmable Josephson voltage standard. To date, many studies have been reported on the circuit design, fabrication, and electrical characteristics of DACs for programmable Josephson voltage standards. In most of those studies, Josephson junctions with Nb electrodes are used [1-3]. At the National Institute of Advanced Industrial Science and Technology (AIST), we have been developing DACs for a programmable Josephson voltage standard using NbN/TiN/NbN junctions [4-6]. Because of the high T_c (15-17 K) of NbN films, DACs with NbN/TiN/NbN junction arrays can be operated with a compact cryocooler [5].

In this paper, we report the circuit design and electrical characteristics of two kinds of DACs fabricated at AIST.

8-bit DACs

The 8-bit DAC consists of a 1-to-8 microwave-distribution circuit, capacitors for dc block, eight arrays containing 4 096 NbN/TiN/NbN junctions each, termination resistors, low-pass filters for rf block, and taps for feeding bias currents and microwaves to the junction arrays. The microwave-distribution circuit is composed of coplanar waveguides with NbN center conductors and NbN ground electrodes. The capacitors for dc block are interdigitated capacitors with a comb structure. Intergigitated capacitors are also used for the low-pass filters. We introduced interdigitated capacitors for improving the problem of superconducting or normal-conducting shorts frequently observed between separated junction arrays of 8-bit DACs in our previous studies. Most of DACs with interdigitated capacitors do not show such shorts. The longest junction array of an 8-bit DAC is divided into 7 segments containing 128, 128, 256, 512, 1 024, 2 048, and 4 096 junctions each and 3 segments having 8 192 junctions each. Bias currents are independently fed to each segment from a current source. The amplitude and the direction of the bias currents are controlled with a computer. The termination resistors are fabricated from a Pd thin film and have resistances of about 50 Ω. Junction area is 3.4 μm-square. Critical current density and the product of critical current and normal-state resistance of a junction are 30 kA/cm ^{2} and 30 μV, respectively. An 8-bit DAC chip has dimensions of 5 mm × 14 mm.

Measurement of electrical characteristics of fabricated DACs is carried out using a two-stage Gifford-McMahon cooler having a water-cooled compressor with a dissipation power of 0.7 kW. Typical cooling time to reach 10 K is 5 hr. Before the measurement, a DAC chip is mounted on a copper plate with a solder with a low-melting point. To ensure a good thermal contact between the chip and the solder, a gold film is sputter-deposited on the back of the wafer at the end of the fabrication process. The copper plate with a DAC chip is mounted on the cold head of the cryocooler via a 2 mm-thick stainless-steel buffer in order to reduce the temperature variation of the chip due to the refrigeration cycle of the cryocooler. The chip is surrounded with two mu-metal cans with different diameters and lengths to minimize the influence of static magnetic fields on junction characteristics.

Despite of the use of the stainless-steel buffer, the temperature of the chip varies with amplitude of 1.0×10^{-1} K corresponding to the refrigeration cycle of the cryocooler. The temperature variation of 1.0×10^{-1} K causes significant reduction in operating margin of a DAC. In order to minimize the temperature variation, we have introduced another DAC as a temperature sensor instead of a CERNOX sensor. Because of the high sensitivity of the DAC sensor for temperature variation, the temperature variation of the chip is reduced to 1.0×10^{-2} K small enough to avoid the lowering of operating margin of a DAC.

Figure 1 shows a current step measured for two junction arrays of an 8-bit DAC by the back-to-back method. Each array contains 4 096 NbN/TiN/NbN junctions in it. In the back-to-back method, two arrays having the same number of junctions are biased in inversed directions each other. The bias current to one array is fixed near

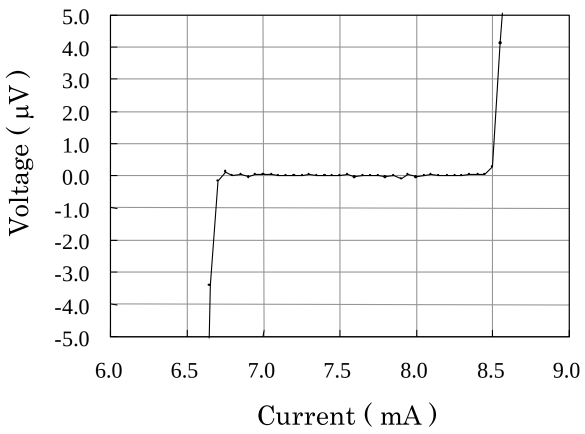

Fig. 1. A current step for an 8-bit DAC at 12.0 K.

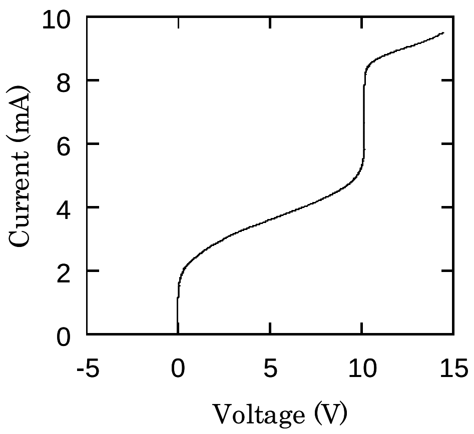

Fig. 2. *I-V* characteristics for an 11-bit DAC at 10.2 K.

the center of a current step and only the bias current to the other is changed and its value is used as the current (*I*) of the current-voltage (*I-V*) characteristics. The voltage (*V*) is measured as the sum of voltages for the two arrays. As a result, if all junctions in the two arrays are normally operated, current steps appear at zero voltages. The current step of Fig. 1 obviously appears at zero voltages. This suggests that the 8 192 NbN/TiN/NbN junctions included in the two arrays are normally operated. The same results are obtained for other arrays of the 8-bit DAC. The frequency of microwaves used in the measurements is 16 GHz and the measurement temperature is 12.0 K. We define the amplitude of a current step as the difference of a current at which 1.0×10^{-7} V appears and a current at which -1.0×10^{-7} V appears. It is found that amplitude of every current step for four pairs of junction arrays of the 8-bit DAC exceeds 1 mA. The highest voltage generated with the DAC is 1.10 V.

11-bitDACs

The 11-bit DACs are fabricated using double-stacked NbN/TiN/NbN/TiN/NbN junctions [4], [6]. This is because integration of more than 300 thousand junctions on a chip is necessary to achieve 10 V-output voltages. The 11-bit DAC consists of a 1-to-32 microwave-distribution circuit, capacitors for dc block, 32 arrays containing 10 240 NbN/TiN/NbN junctions each, termination resistors, low-pass filters for rf block, and taps for wiring. The longest junction array of an 11-bit DAC is divided into 22 segments. Seven of the 22 segments have 320, 320, 640, 1 280, 2 560, 5 120, and 10 240 junctions each. Fifteen segments have 20 480 junctions each. The 11-bit DAC has dimensions of 15-mm square.

Figure 2 shows *I-V* characteristics measured for an 11-bit DAC by biasing 16 GHz microwaves to all of the 22 segments of the DAC, providing proper amplitude of DC currents to 21 segments each, and providing zero-DC currents to one segment that has 20 480 junctions. The reason for excluding one segment from the measurement is that clear current steps are not observed for the segment. At the present stage, the origin of the failure is not clear. Step amplitude greater than 1 mA is obtained for all of 21 segments measured. This indicates high uniformity is achieved in critical current and normal-state resistance for each of junction arrays included in the 21 segments. The highest voltage generated with the 11-bit DAC is 10.16 V.

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