Superconductor-Normal-Superconductor Junctions for Digital/Analog Converters

S. P. Benz
National Institute of Standards and Technology, Boulder, CO 80303

Abstract— Series arrays of Nb-PdAu-Nb Josephson junctions have been fabricated with characteristics ideally suited for application in programmable voltage standards and digital/analog converters. Large arrays of junctions with applied microwave power showed constant voltage steps with current amplitudes as large as 7 mA. A novel coplanar waveguide design has enabled uniform microwave power coupling to a 5-segment array of 8192 total junctions so that each array segment has constant voltage steps over the same bias current range. The 8192-junction device generated 1.1 mA steps at 186 mV with 11 GHz power and a maximum constant voltage step of 260 mV at 15.34 GHz.

I. Introduction

A fast programmable voltage standard has application for ac metrology, precision waveform synthesis, and characterization of high-precision D/A and A/D converters. Such a device can be made by exploiting the ac Josephson effect; when an ac current at frequency f is applied across a Josephson junction, the current-voltage (I-V) curve exhibits equally spaced constant voltage steps at voltages $V = nf/K_J$, where K_J = 483 597.9 GHz/V is the Josephson constant and n is an integer. The appropriate bias condition for programmable voltage standards has the microwave power adjusted to simultaneously maximize the current amplitudes of the n = 0 and ±1 steps. A 12-bit D/A converter was recently demonstrated by Hamilton et al. [1] as a rapidly programmable voltage standard using a binary sequence of series arrays of nonhysteretic resistively shunted tunnel junctions (see Fig. 1). Each Nth segment (or bit) required a series array of 2^N junctions capable of producing constant voltages at 0 and $\pm 2^N f/K_J$. This device was used to digitally synthesize ac waveforms.

Superconductor-normal-superconductor (SNS) junctions have been theoretically [2-3] and experimentally [4-5] investigated for this application in both low-T_c and high-T_c technologies. SNS junctions have a number of advantages over resistively shunted tunnel junctions. Their higher critical currents (I_c > 1 mA) provide greater stability against thermal fluctuations, greater output current, and faster slew rates. Second, their lower characteristic voltages (I_cR, where R is the junction resistance) imply lower operating frequencies, which enable ~20 μV resolution and less expensive microwave electronics. The third advantage is that SNS junctions are available in high-T_c technology so that the devices might be operated at higher temperatures.

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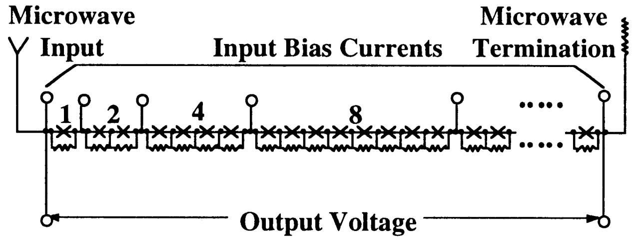

Fig. 1: A Josephson D/A converter based on a binary sequence of junction arrays.

The primary disadvantage of SNS junctions, compared to the tunnel junctions used in existing dc voltage standards, is that their high microwave losses complicate the problem of providing uniform ac power distribution to each junction in the device. This paper presents two experimental advances in low-T_c programmable voltage standards: the demonstration of uniform arrays of SNS junctions with large step amplitudes and the demonstration of a coplanar wave guide (CPW) design that provides uniform microwave power to a multi-segment array of 8192 SNS junctions.

II. Uniform Arrays of SNS junctions

Fabrication of Nb-PdAu-Nb junctions was accomplished using a standard trilayer geometry, consisting of 220 nm-thick Nb base-electrode, 30-50 nm-thick PdAu (53 % Pd:47 % Au by weight) barrier, and 110 nm-thick Nb counter-electrode. Nb wiring contacts to the counter electrode were made through 1-μm-diameter via holes in 350 nm-thick SiO_2. The PdAu barrier was wet-etched and the Nb and SiO_2 layers were reactive-ion-etched. PdAu pads and resistors were lifted off. Series arrays of 400 junctions with square counter-electrode dimensions ranging from 1 to 10 μm were used to characterize the SNS junction technology. Using Van der Pauw test structures and series arrays of junctions [6], we found the PdAu resistivity ρ = 417 mΩ•μm and the current density as a function of barrier thickness $J_c(t)$ = (385 mA/μm^2) exp(-t/ 6.6 nm).

Surprisingly, the junctions are very uniform in critical current and characteristic voltage in spite of the exponential barrier thickness dependence. On a given 1 cm × 1 cm chip, we find that uniformity is consistent with lithographic variations, as in trilayer tunnel junctions (< 5 % at 1σ) [6]. On-chip junction uniformity is therefore sufficient for this application. However, the exponential thickness dependence is apparent across a 76 cm (3 in) wafer since our 76 cm diameter magnetron deposits the PdAu over the same size wafer with 5-10 % thickness uniformity.

Figure 2a shows the *I-V* curve for a 400 junction series array of 2.5 μm × 2.5 μm junctions with $t \approx 37$ nm. $I_C \approx 10.4$ mA and $R \approx 1.8$ mΩ. Estimating the Josephson penetration depth $\lambda_J \approx 0.87$ μm, we find that the junction diameter $l \approx 2.9\lambda_J$ is close to the optimum value for producing large amplitude steps without excessive microwave power [3].

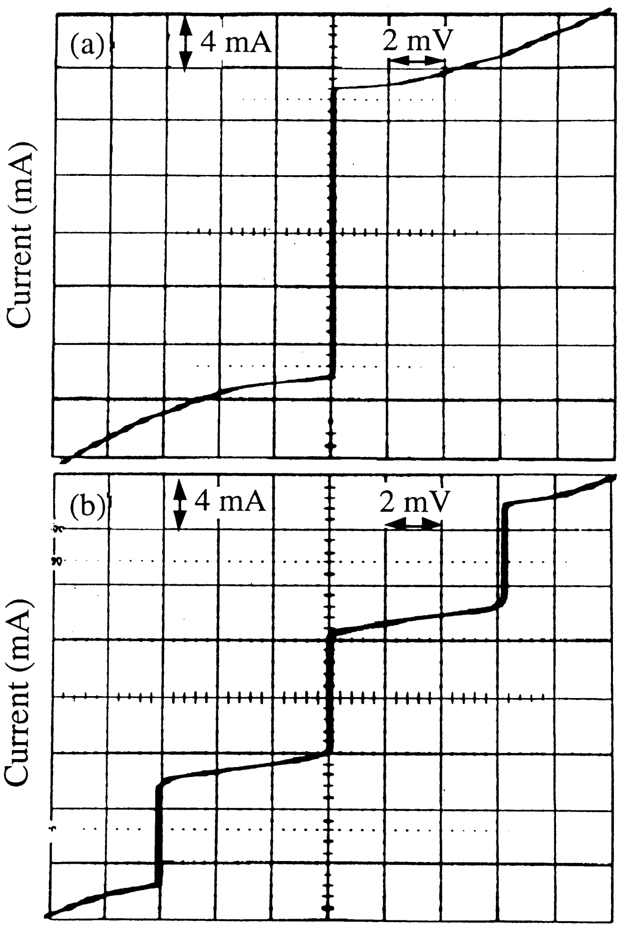

Fig. 2: Current-voltage characteristics for a 400-junction SNS series array at 4 K (a) with no microwave power and (b) with microwave power at 7.5 GHz.

Microwaves were coupled through the bias leads of these arrays. Figure 2b shows the array when microwave power at 7.5 GHz is adjusted to simultaneously maximize the amplitudes of the $n = 0$ and ± 1 steps. An accurate measurement of the array voltage on the first step at 6.2 mV confirms that all 400 junctions are on the first step. The large 7 mA step amplitudes observed here are a 140-fold improvement over the 50 μA steps typical of resistively shunted tunnel junctions [1], demonstrating a clear advantage of SNS junctions. Several milliamperes can be drawn from this array without affecting its voltage.

The microwave power uniformity and junction uniformity for these arrays is apparent from the sharp corners of the steps, suggesting that uniformity is sufficient for much larger arrays and possibly even smaller junction areas. These encouraging results led us to pursue larger arrays of junctions and to explore methods for uniform microwave power coupling in multi-segment SNS array circuits.

III. Uniform Microwave Power Distribution

In order to investigate uniform power coupling in multi-segment circuits, and encouraged by the surprising uniformity of the previous arrays, we investigated circuits without ground planes and CPW circuits. The main problem in multi-segment circuits is maintaining microwave power uniformity in spite of multiple dc bias leads. None of the circuits without ground planes were successful in achieving uniform power distribution either within a given segment or between segments in the circuit. These results confirm our hypothesis that coupling to our previous circuits occurred primarily through the bias leads, but show that this method is inappropriate for multi-segment circuits. Fortunately the CPW circuits on the same wafer were more successful.

A 50 Ω CPW design was investigated to couple microwave power to a multi-segment circuit. A semirigid coaxial cable coupled the microwaves from room temperature to CPW on a BeCu finger board. BeCu spring fingers contacted PdAu-covered Nb pads on the chip. An exponential Nb taper transformed the off-chip CPW to a splitter having two branches of 50 Ω CPW with a 6 μm-wide center conductor. 18 μm-wide ground conductors were spaced 3 μm on either side of the center conductor. 4096 junctions were placed in series along the center conductor of each branch. One branch consisted of the most significant bit having 4096 junctions. The other branch was segmented into arrays with 2048 and 1024 junctions and two arrays with 512 junctions. Each branch makes three 180° bends and is terminated with a 48 Ω resistor. DC bias leads to each segment are filtered using 11 GHz quarter-wavelength stubs with 7 pF termination capacitors to keep the microwave power in the waveguide at this design frequency. When all 5 segments are biased, a series array of 8192 junctions is obtained. The 2 μm × 2 μm junctions have 1.9 mA critical currents and 4.4 mΩ resistances.

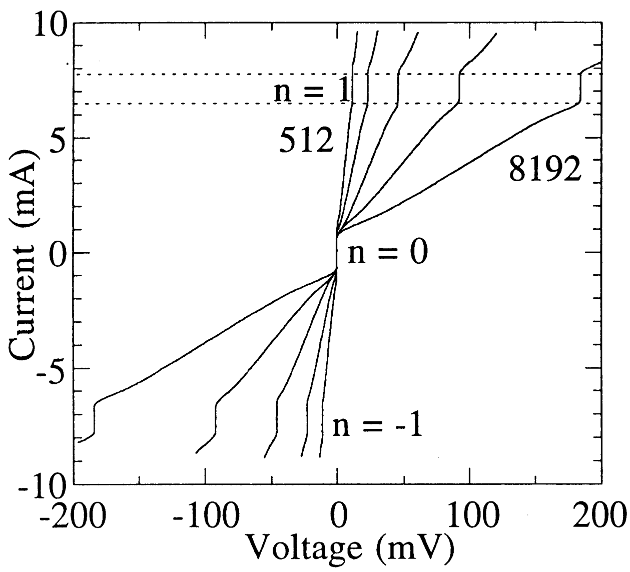

Fig. 3. Current-voltage characteristics for the 4 binary sequence of segments (512, 1024, 2048, and 4096 junctions), and for the entire 8192 junction array at 11 GHz.

Figure 3 shows the *I-V* curves separately for each of the different segments and for the entire array when biased with 11 GHz microwave power. The power and junction uniformities are both sufficient to operate all segments at the same microwave power and dc bias. This is the ideal operating condition for the programmable voltage standard.

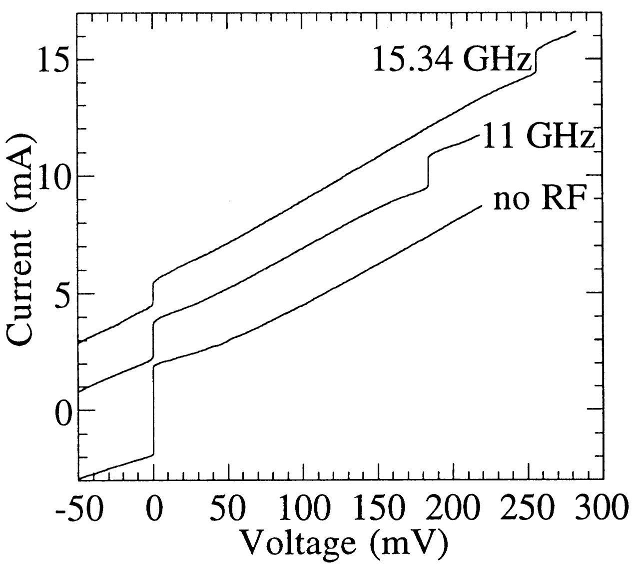

Fig. 4. Current-voltage characteristics for the 8192 junction array with (a) no microwaves, (b) 11 GHz and (c) 15.34 GHz. (b) is offset by 3 mA. (c) is offset by 5 mA.

Figure 4 compares the *I-V* curve of the entire 5-segment device, all 8192 junctions, with no microwaves, at 11 GHz, and at 15.34 GHz, which is substantially above the design frequency. At 11 GHz the $n = 0$ and 1 step amplitudes are 1.34 mA and 1.1 mA respectively, for this nearly optimized power. The reduction in step amplitudes from the expected maximum of about 2 mA cannot be accounted for with junction dissipation, suggesting that some power loss to the bias leads still occurs. At frequencies away from the 11 GHz design frequency, as in the 15.34 GHz data, the most important source of power nonuniformity probably arises from power loss to the bias leads; the maximum step amplitudes at 15.34 GHz are reduced to 0.75 mA compared to those at the design frequency.

IV. Conclusions

PdAu trilayer SNS junctions can be made with sufficient critical current and uniformity to be considered as strong candidates for programmable voltage standard applications. Sufficiently uniform microwave power coupling has been achieved in large multi-segment arrays of SNS junctions using a coplanar waveguide design. Further improvements in power uniformity may be obtained by improving the bias lead filters.

Although many more junctions are required to achieve 1-10 V for low-I_cR SNS technology, the CPW design has fewer fabrication layers (one less insulating and metal layer) than shunted junction technology and should enhance the yield for large arrays of SNS junctions. For the same reasons, the CPW design should simplify realization of programmable voltage standards with high-T_c materials. With only a factor of 4 increase in the number of junctions, it should be possible to demonstrate a programmable voltage standard with a range of ±1 V, 15-bit resolution, and 30-bit accuracy (0.4 ppm).

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EXTENDED ABSTRACTS

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