AIP | Applied Physics Letters

Superconductornormalsuperconductor junctions for programmable voltage standards

S. P. Benz

Citation: Applied Physics Letters **67**, 2714 (1995); doi: 10.1063/1.114302
View online: http://dx.doi.org/10.1063/1.114302
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/67/18?ver=pdfcov
Published by the AIP Publishing

Superconductor-normal-superconductor junctions for programmable voltage standards

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

(Received 1 August 1995; accepted for publication 5 September 1995)

Series arrays of Nb–PdAu–Nb Josephson junctions were fabricated with characteristics ideally suited for application in programmable voltage standards and D/A converters with fundamental accuracy. 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 enabled uniform microwave power coupling to a five-segment array of 8192 junctions, so each segment had constant voltage steps over the same bias 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.

In this letter, two experimental advances in low-T_c programmable voltage standards are demonstrated. First, arrays of Nb–PdAu–Nb Josephson junctions are shown to have uniform critical currents, and the current amplitudes of microwave-induced constant voltage steps are shown to be as large as 7 mA. Second, we demonstrate a coplanar wave guide design with uniform microwave power distribution to a multisegment array of 8192 junctions.

The present Josephson array voltage standard is based on the ac Josephson effect;[1] when an ac current at frequency f is applied to 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. About 20 000 junctions are driven at 75 GHz to generate steps spanning the range from -14 to $+14$ V. Unfortunately, the procedure to select a particular step is so slow that these standards are useful only for dc measurements.

A new Josephson circuit that allows the rapid selection of any step number was recently demonstrated by Hamilton *et al.*[2] This rapidly programmable voltage standard is a D/A converter that uses a binary sequence of $N=14$ series arrays of nonhysteretic resistively shunted tunnel junctions. The appropriate bias condition for this circuit has the microwave power adjusted to simultaneously maximize the current amplitudes of the $n=0$ and ±1 steps. Each Nth segment (or bit) consists of a series array of 2^N junctions capable of producing constant voltages at 0 and $\pm 2^N f/K_J$. The voltage across all segments adds in series. Thus, any output voltage between $-2^{N+1}f/K_J$ and $+2^{N+1}f/K_J$ in steps of f/K_J can be selected by choosing appropriate bias currents for the array segments. The new circuit was used to digitally synthesize ac wave forms. Fast programmable voltage standards have application for ac metrology, precision wave form synthesis, and characterization of high-precision D/A and A/D converters.

Superconductor-normal-superconductor (SNS) junctions have been theoretically[3,4] and experimentally[5,6] investigated for programmable standards 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.[2–4] Second, their lower characteristic voltages (I_cR, where R is the junction resistance) imply lower operating frequencies, which enable $\sim 20\ \mu$V 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. The primary disadvantage of SNS junctions and shunted tunnel junctions over the unshunted 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.

Fabrication of Nb–PdAu–Nb junctions was accomplished using an *in situ* deposited trilayer, consisting of a 220 nm-thick Nb base electrode, 30 to 50 nm-thick PdAu (53% Pd:47% Au by mass) 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 electrodes ranging from 1 to 10 μm were used to characterize the SNS junctions. Using van der Pauw test structures we found the PdAu resistivity $\rho=417$ m$\Omega\ \mu$m at 4 K.[7] Measurements on series arrays of junctions showed the current density as a function of barrier thickness to be $J_c(t)=(385\ \text{mA}/\mu\text{m}^2)\ \exp(-t/\ 6.6\ \text{nm})$.

In spite of the exponential barrier thickness dependence, the junctions are very uniform in critical current and characteristic voltage. 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).[7] On-chip junction uniformity is sufficient for this application. However, the exponential thickness dependence is apparent across a 76 mm (3 in.) wafer since our 76 mm-diameter magnetron deposits the PdAu over the same size wafer with 5%–10% thickness uniformity.

Figure 1(a) shows the I–V curve for a 400 junction series array of 2.5 μm × 2.5 μm junctions with $t\approx37$ nm. $I_c\approx10.4$ mA and $R\approx1.8$ mΩ. Estimating the Josephson penetration depth $\lambda_J\approx0.87\ \mu$m, we find that the junction diameter $l\approx2.9\lambda_J$ is close to the optimum value for producing

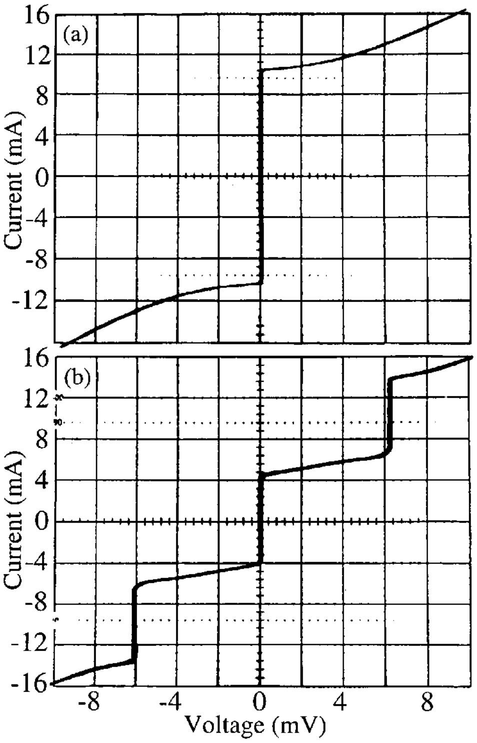

FIG. 1. Current–voltage characteristics for a 400-junction SNS series array at 4 K (a) with no microwave power and (b) with microwave power at 7.5 GHz.

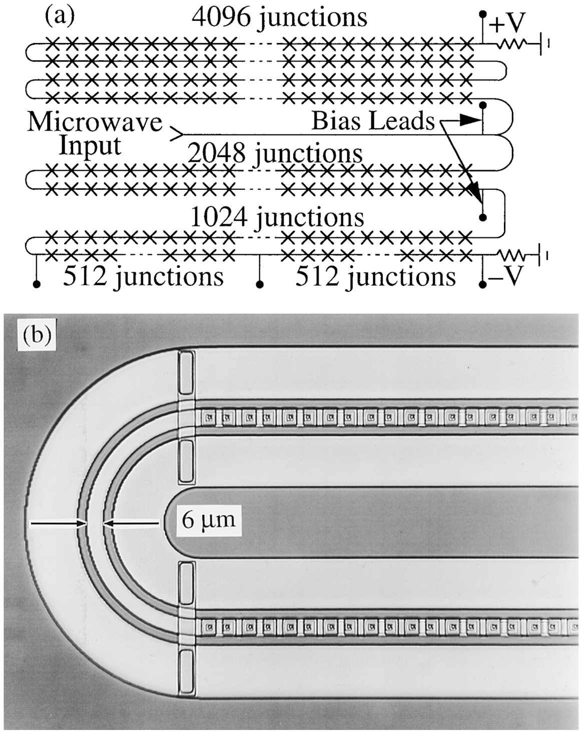

FIG. 2. (a) Schematic of segmented array showing binary sequence of junctions. (b) Photograph showing 180° CPW bend, series junctions on center conductor, and two lithographic air bridges.

large amplitude steps without excessive microwave power.[4]

Microwaves were coupled to the bias leads of these arrays using a single-turn, 1 cm diameter coil over the chip. Figure 1(b) 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,[2] 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 of these arrays are 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 multisegment SNS array circuits.

In order to investigate uniform power coupling in multisegment circuits, and encouraged by the surprising uniformity of the previous arrays, we investigated circuits without ground planes and coplanar wave guide (CPW) circuits. The main problem in multisegment 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 inductive coupling to our previous circuits occurred primarily through the bias leads, but show that this method is inappropriate for multisegment circuits. Fortunately the CPW circuits on the same wafer were more successful.

A CPW design was investigated to couple microwave power to a multisegment circuit (see Fig. 2). A semirigid coaxial cable coupled the microwaves from room temperature to a 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 separated by 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. The series connection of all five segments forms a series array of 8192 junctions. The 2 μm × 2 μm junctions have 1.9 mA critical currents and 4.4 mΩ resistances.

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 on-chip power distribution and junction critical currents were both sufficiently uniform to operate all segments at the same microwave power and dc bias. This is the ideal operating condition for the programmable voltage standard.

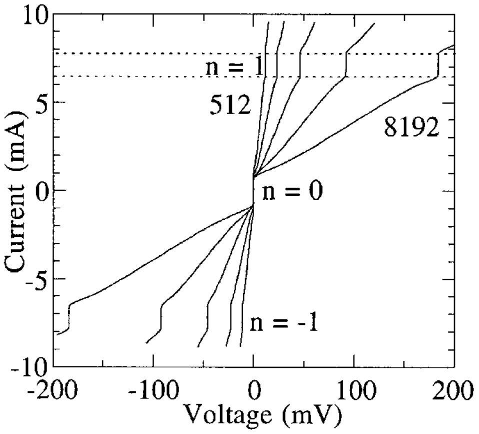

FIG. 3. Current–voltage characteristics for the four binary sequence of segments (512, 1024, 2048, and 4096 junctions), and for the entire 8192 junction array at 11 GHz.

Figure 4 compares the *I*–*V* curve of the entire five-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 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 by 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.

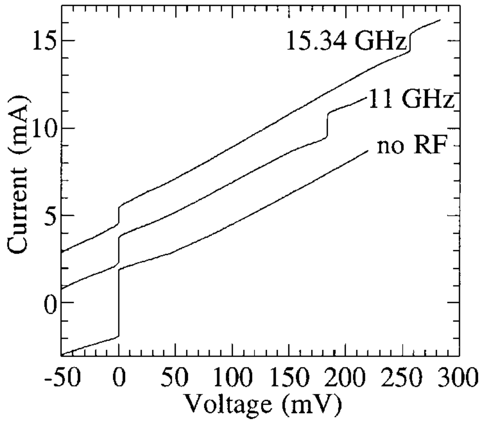

FIG. 4. Current–voltage characteristics for the 8192 junction array with (a) no microwaves, (b) 11 GHz, and (c) 15.34 GHz. (b) is offset by 3 mA. (c) is offset by 5 mA.

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

Many more junctions are required to achieve 1 to 10 V for SNS programmable voltage standards than for shunted tunnel junction designs. However, the CPW design has fewer fabrication layers (one fewer insulating and one fewer metal) than microstrip designs 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.

The author thanks C. Hamilton, R. Kautz, D. DeGroot, P. Booi, and R. Ono for discussions. This research was supported in part by the CCG.

[1] C. A. Hamilton, C. Burroughs, and K. Chieh, J. Res. Nat. Inst. Stand. Technol. **95**, 219 (1990).

[2] C. A. Hamilton, C. J. Burroughs, and R. L. Kautz, IEEE Trans. Instrum. Meas. **44**, 223 (1995).

[3] R. L. Kautz, J. Appl. Phys. **76**, 5538 (1994).

[4] R. L. KautzJr, J. Appl. Phys. **78**, 5811 (1995).

[5] R. L. Kautz, S. P. Benz, and C. D. Reintsema, Appl. Phys. Lett. **65**, 1445 (1994).

[6] S. P. Benz, C. D. Reintsema, R. H. Ono, J. N. Eckstein, I. Bozovic, and G. F. Virshup, IEEE Trans. Appl. Supercond. **5**, 2915 (1995).

[7] J. E. Sauvageau, C. J. Burroughs, P. A. A. Booi, M. W. Cromar, S. P. Benz, and J. A. Koch, IEEE Trans. Appl. Supercond. **5**, 2303 (1995).