Stacked SNS Josephson Junctions for Quantum Voltage Applications

Paul D. Dresselhaus, Yonuk Chong, and Samuel P. Benz

Abstract—**NIST is using superconducting-normal-metal-superconducting Josephson junctions as the basis of quantum voltage metrology. Planar junction technology limits the voltage and bandwidth of these systems due to parasitic inductances and the transit time of waveforms through the transmission line. By using stacked junctions, we are able to pack junctions more closely in a transmission line while maintaining the uniformity needed for voltage-standard applications.**

We discuss the technological advantages in stacking multiple junctions and present data from stacked junctions. The normal metal used for these stacked junction arrays is $MoSi_2$. Stacked junctions using this barrier material have demonstrated excellent uniformity and etch characteristics similar to those of niobium. We present measurements of synthesized ac waveforms made with arrays of double junction stacks.

I. INTRODUCTION

THE use of arrays of over-damped junctions for voltage standards has been the focus of much recent work. Since Josephson junctions are perfect frequency-to-voltage converters, and because accurate frequency standards are common, arrays of Josephson junctions make excellent dc voltage standards [1-3]. The same reasoning in the time domain has led to the use of Josephson arrays for synthesis of precision ac voltage waveform [4, 5].

A major limitation on arrays of Josephson junctions is their linear density. Junction arrays of higher density would allow either more junctions to be fit into the same length of array, or the same number of junctions to fit into a smaller length. The maximum number of junctions in an SNS array is limited by the dissipation of the junctions [5]. Arrays of smaller length have better operating margins because of the increase in the minimum frequency that causes standing waves (created by various discontinuities). The net result of higher junction density is either larger voltage (from more junctions) or increased operating margins (from shorter transmission-line length). Programmable voltage standards could benefit from stacked arrays by an N-fold increase in output voltage for an N-junction stack. AC voltage standards can benefit from both larger operating margins and higher voltages.

Junction arrays embedded in a transmission line also have parasitic inductances due to via structures or the three-dimensional nature of the current flow. When these inductances are driven with ac currents, they generate erroneous output voltages. In order to minimize parasitic inductances, it is also desirable to have the highest possible junction density and the fewest total number of stacks and vias.

In addition, higher junction density leads toward the goal of lumped arrays, where the array then acts as a single 50 Ω microwave element [6]. This would not only eliminate many common-mode measurement errors, but would also allow all of the microwave power to be dissipated in the array, instead of in the termination resistors, which add undesirable heat to the circuit.

The Josephson Arbitrary Waveform Synthesizer (JAWS) is a realization of voltage-standard technology for arbitrary waveforms. To produce dc signals, a microwave sine wave is used. If this sine wave is modulated with a digital code, both positive and negative flux-quantum pulses occur, which allows arbitrary waveforms to be produced by use of appropriate digital codes [5]. In this paper, the digital code is chosen to produce an audio sine wave that has a frequency 1/3,000,064 of the clock frequency of the digital code. For proper synchronization, the microwave sine frequency is chosen to be either 3/2 or 5/2 of the digital code clock frequency.

II. RESULTS

Two-junction stacks with Nb superconducting electrodes and $MoSi_2$ barriers were grown on oxidized Si wafers. The fabrication details are published elsewhere [7]. The junctions for this work are 5.5 μm x 6 μm with 23 nm barriers. The thicknesses of the Nb electrodes are (from bottom to top) 330 nm, 50 nm, and 200 nm. The junctions are operated at 4 K in a liquid helium probe. The characteristic voltage of these

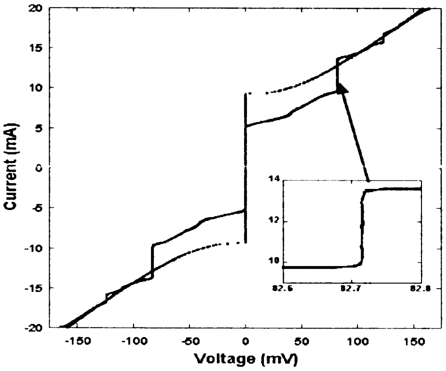

Fig. 1. Current-voltage characteristics of a two-junction x 1000-stack array. The trace represented by the solid curve has a 20 GHz microwave bias, while the trace represented by the dotted curve has no microwave signal applied. The sharp transitions and large steps are indications of good junction uniformity.

P.D. Dresselhaus, Y. Chong, and S.P. Benz are with the National Institute of Standards and Technology, Boulder, CO 80305 USA (303-497-5211;fax: 303-497-3042; e-mail: paul.dresselhaus@nist.gov).

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junctions is 39 uV.

Figure 1 shows the current-voltage characteristics of a 1000-stack array of double-junction stacks (a total of 2000 junctions) with 20 GHz microwave radiation applied, and without microwaves. There is a large clear step (enlarged in the inset) at the proper voltage. The current range of this step indicates the high degree of uniformity in the array, which could be degraded by such things as lithographic, etch non-uniformities or standing waves. It should also be noted that the transition to the voltage state in the dc curve is very sharp at the critical current, another qualitative sign of good junction uniformity.

The arrays were also tested with a broad range of microwave frequencies between 3 GHz and 18 GHz to see whether there were any resonances in the microwave structures. Adding filters at the taps of the microwave structures is necessary to keep the power inside the array's coplanar waveguide transmission line and to prevent formation of standing waves caused by impedance discontinuities from the bias taps. The bias taps should pass only the low-frequency part of the signal, and they should block the microwave power so that it remains in the transmission line and uniformly biases the entire array. The filters on the bias taps are a series of six on-chip coil inductors, each approximately 3 nH. These filters provide microwave filtering sufficient to remove most of the resonances in the 3 GHz – 18 GHz range, such that these circuits are viable candidates for the JAWS system.

For the JAWS measurements, the sine-wave frequency was chosen to correspond to a large microwave step, as in the 18.5 GHz step shown in Fig. 1. The digital code was operated at 2/5 of this frequency, or 7.4 GHz; thus the resulting audio sine wave was at 2.47 kHz. The measured power spectrum is shown in Fig. 2. The distortion on this spectrum was measured by the maximum harmonic amplitude–in this case the second harmonic, which is 95 dB below the fundamental (-95 dBc). This type of spectral purity is typical of the JAWS system. Measuring distortion at these levels is difficult because the analog-to-digital converter in the spectrum analyzer is specified only to -88 dBc. The peak amplitude of the synthesized sine wave was chosen to be 95 % of the n=1 step, or 72.7 mV. Arrays with more junctions are needed to reach the higher voltages for practical applications [8].

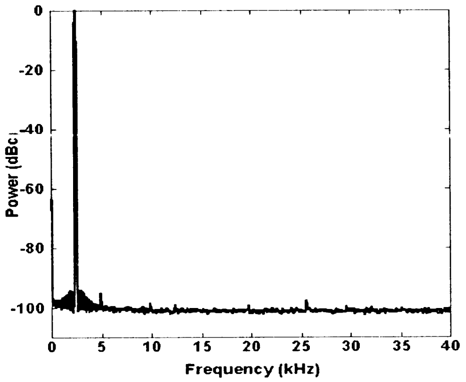

Fig. 2 Power spectrum of the JAWS for a 2.47 kHz sine wave where the amplitude is measured with respect to that of the fundamental. The highest distortion is seen in the second harmonic, which has 95 dB less power than the fundamental frequency (-95 dBc).

Qualitatively, the circuit exhibited larger operating margins than similar circuits that use PdAu barriers [8]. Operating margins are defined as the variations in the input parameters over which the circuit will continue to operate with identical output. These increased margins may be due to the larger junction size, and thus better uniformity-even though the junction patterning step must etch through both barriers. Increased margins could also be due to a relative increase in the reactive part of the shunting due to the higher resistivity of $MoSi_2$, a shorter transmission line, fewer vias and a smaller parasitic inductance.

The improved margins also enabled higher frequency operation. These stacked arrays yielded a synthesized sine produced with the highest microwave sine frequency used to date in a JAWS–synthesized waveform, 18.5 GHz. Higher frequencies lead to higher voltage, which is another advantage of using the $MoSi_2$ barrier stacks.

III. CONCLUSION

Arrays of double-stacked junctions have been measured in the JAWS system for producing quantum-defined ac waveforms. Stacked-junction arrays appear to be well suited for this application, which leads to the possibility of improved operating margins and higher voltages. The demonstrated higher operating frequency will also lead to our goal of higher voltages.

Stacked junctions or arrays can now be used in any circuit where a single junction was previously used. These could double the output voltage of the programmable voltage standard as well as increase the voltage of the JAWS system. It also continues the improvement in junction technology that will ultimately lead to the use of stacked junction arrays as lumped elements in Josephson array circuits.

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