Arrays of High-Temperature Superconductor Josephson Junctions for a Quantized Voltage Noise Source

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***Abstract*—We have investigated arrays of high-temperature superconducting $YBa_2Cu_3O_7$ (YBCO) bicrystal Josephson junctions for application in a quantized voltage noise source. In order to reduce the intrinsically high 100-150 GHz characteristic frequency of bicrystal junctions to the low 5 GHz drive frequency of the digital pulse-drive signal used in this source, we examined different designs where gold films deposited on top of the YBCO films were used to shunt the junctions. From the dc characteristics we observe a 10-fold decrease in the characteristic frequency as compared with that of the unshunted junctions. We discuss methods to further decrease the characteristic frequency to achieve the 5 GHz target frequency.**

I. Introduction

The Josephson arbitrary waveform synthesizer has been successfully adapted as a quantized voltage noise source (QVNS) for calibrating the cross-correlation electronics of a Johnson noise thermometer system [1-3]. The main part of the QVNS is a pulse-driven Josephson digital-to-analog converter based on arrays of nonhysteretic Josephson junctions. By creating perfectly quantized pulses, the QVNS produces calculable ac voltage signals of small amplitude with quantum accuracy. Performance of the QVNS could be improved by decreasing the length of the output transmission lines. The system would also be easier to use if it operated at higher temperature, in particular in liquid nitrogen. These advantages, in addition to the fact that only a small number of junctions are necessary, have motivated us to consider high-tem-perature superconductor (HTS) $YBa_2Cu_3O_7$ (YBCO) shunted bicrystal Josephson junctions for the QVNS application arrays [4]. The primary challenge in using these bicrystal junctions is to decrease the characteristic frequency of the junctions to match them to the relatively low 5 GHz drive frequency f of the broadband two-level digital signal that drives the array. In order to decrease the characteristic frequency, the bicrystal junctions were shunted by depositing a gold film on top of the $YBa_2Cu_3O_7$ (YBCO) superconductor. Unfortunately, the characteristic frequency of the measured arrays appears to be higher than that expected from the dc current-voltage characteristics. In order to investigate this limitation, different circuit designs of single junctions and arrays were fabricated and measured.

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II. Optimization of Junctions Parameters

The typical characteristic frequency of unshunted bicrystal junctions at 77 K is typically in the range of 100-150 GHz for misorientation angles of 24° and 19°[4]. For the successful application of arrays of bicrystal junctions in the QVNS, the characteristic frequency of junctions should be decreased 20-fold. According to the resistively shunted junction (RSJ) model, when the drive frequency matches the characteristic frequency the step amplitude ΔI_1 approaches the value of the junction critical current I_c. At the same time ΔI_1, and therefore I_c, should be at least 1 mA to minimize the influence of thermal noise at liquid nitrogen temperatures.

In order to achieve these requirements, we made single shunted Josephson junctions and arrays using a bicrystal substrate covered with a Au-YBCO bilayer [5]. We fabricated HTS bridges with width w_s, meander height L_s and distance between bridges l_s as shown in Fig.1. The patterned microbridges cross the grain boundary (GB), thus forming Josephson junctions. The corresponding shunt dimensions, w_{sh}, L_{sh}, and l_{sh}, of the gold film typically coincide with the HTS meander dimensions, but we have also made the shunt dimension slightly larger. In the latter case an additional gold film layer is evaporated on top of the bilayer.

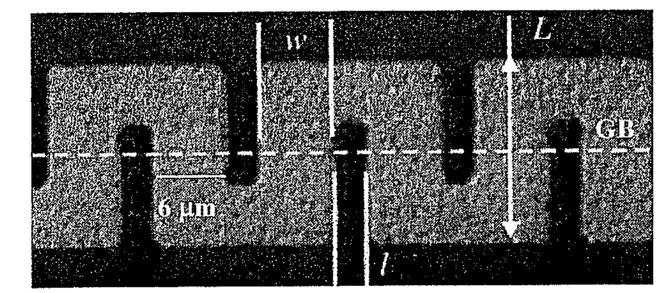

Fig. 1. A part of an array of shunted bicrystal junctions

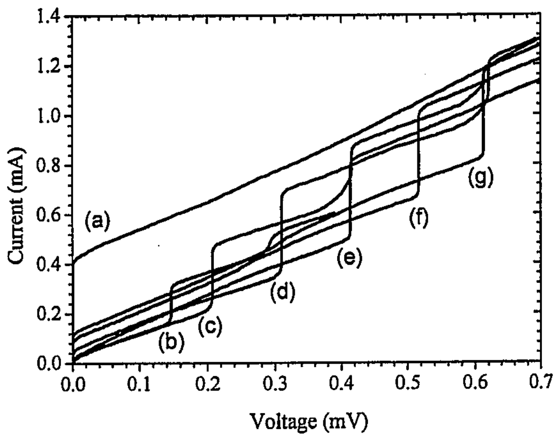

Fig. 2. Dependence of the first voltage step on irradiation frequency of an array of 10 series connected shunted bicrystal junctions at 77 K: (a) without irradiation; (b) with irradiation at frequency 7.1 GHz; (c) 10 GHz, (d) 15 GHz, (e) 20 GHz, (f) 25 GHz and (g) 30 GHz.

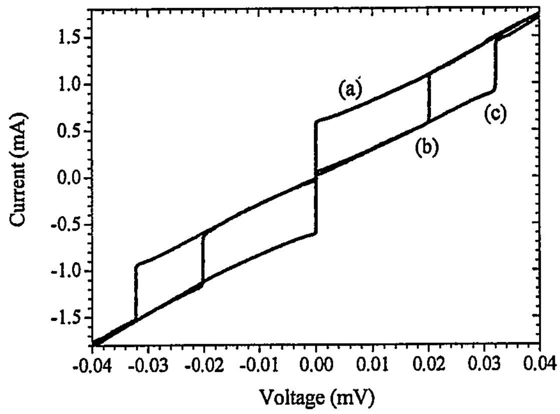

Fig. 3. Dependence of the first voltage step on irradiation frequency of a single shunted bicrystal junction at 77 K: (a) without irradiation; (b) with irradiation at frequency 9.8 GHz and (c) 15.6 GHz.

The gold film is distributed over the circuit and is not a discrete external shunt element in which there typically exists a parasitic inductance. In our case, due to the existence of the bicrystal grain boundary, the current flows partially through the Au layer and partially through the YBCO film. The shunt's resistance should be much smaller than the junction's intrinsic normal resistance. This is accomplished by increasing the Au thickness or adjusting the meander dimensions [6]. The interface resistance between the Au and YBCO films should also be taken into account.

To explore the shunted junction characteristics we have investigated single junctions and arrays with dimensions of $w = 6$ μm, $L = 10$ μm and $l = 2$ μm. Fig. 2 shows the current-voltage *IV* curves of a 10 junction array (a) without, and (b)-(g) with microwave bias. Based on an RSJ-model analysis of the dc *IV* curve (a) we estimated the critical current of the array, I_c=0.38 mA, and the average resistance per junction, $R = 0.065\ \Omega$. This yields an estimate of the characteristic frequency, $f_c \approx 12$ GHz.

Note that the n=1 constant voltage step height increases with the drive frequency even above the characteristic frequency. We believe that this is not due to junction or microwave bias non-uniformity, but due to the real junction dynamics. We conclude that the estimated f_c is incorrect and that the simple RSJ model is insufficient for these junctions. These effects are confirmed by measurements of single junctions, and indicate that the actual characteristic frequency of the junctions is much larger than 12 GHz. We also suppose that the real characteristic frequency of these shunted grain-boundary junctions must be at least 30 GHz, corresponding to $2.5f_c$ of the dc estimated characteristic frequency. At this frequency the step height ΔI_1 was equal to 0.3 mA or 80 % of I_c.

In order to further decrease the true characteristic frequency we increased the dimensions w_{sh}, L_{sh}, and l_{sh} of the Au layer such that they were 4 μm larger than the corresponding dimensions of the YBCO meander. In this case the distance between the junctions was equal to $l_s = 6$ μm. Furthermore, the YBCO film thickness was increased in order to increase I_c. Fig. 3 shows the *IV* curves of a single junction (a) without, and (b), (c) with microwave bias. From curve (a) we estimate $f_c \approx 6.5$ GHz and $I_c = 0.58$ mA. The dc characteristic frequency is two-times smaller compared to the previous arrays where the gold and YBCO films had the same dimensions. In curve 3(b) with $f \approx 10$ GHz ($1.5f_c$) we observe that the height of the first step is 0.44 mA or 74 % of I_c. While in curve 3(c) the higher frequency of 15.6 GHz ($3\ f_c$) drive produces a step height of 0.55 mA nearly equivalent to the critical current (95 % I_c). It appears that the larger Au film effectively decreases the characteristic frequency, although the real characteristic frequency still appears to be 1.5 to 3 times larger than that estimated from the dc *IV* curve.

III. Conclusion

We have demonstrated shunted bicrystal junctions with critical currents greater than 0.5 mA and estimated characteristic frequencies in the range 10 GHz to 15 GHz. This range is ten times smaller than the corresponding parameter for the unshunted junctions but is still two times larger than our target characteristic frequency of 5 GHz. Further two-fold decrease in f_c and two-fold increase of I_c should be possible by increasing the dimensions of the gold film in comparison with the HTS film. Decreasing the distance l_{sh} between the gold bridges to submicrometer lengths could also further decrease f_c.

References

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