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Metallic-barrier junctions for programmable Josephson voltage standards [1]

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Abstract. The current amplitudes of Shapiro steps are studied in large-area metallic-barrier Josephson junctions by simulation and experiment. In the absence of a ground plane, simulations show that junctions larger than about 4 times the Josephson penetration depth are of limited utility because the microwave power required to induce Shapiro steps increases rapidly with junction size. Experimentally, step amplitudes as large as 7 mA are observed in Nb–PdAu–Nb sandwich junctions.

1. Introduction

Recently, Hamilton *et al.* [1] demonstrated a rapidly programmable voltage standard consisting of a series array of nonhysteretic Josephson junctions. While the principal advantage of this standard is that it can be programmed rapidly enough to synthesize accurate low-frequency waveforms, additional advantages result if metallic-barrier, or superconductor-normal-superconductor (SNS), junctions are employed. In particular, SNS junctions circumvent a restriction on critical current imposed on both the hysteretic junctions used in zero-bias arrays [2] and the shunted tunnel junctions used in the prototype programmable array [1]. Instead of being limited to a fraction of 1 mA, the useful critical current of SNS junctions can be several milliamperes, resulting in a voltage standard with large-amplitude Shapiro steps, high output currents, and more stable operation. In this paper we use both theory and experiment to explore the maximum step amplitude attainable in SNS junctions having the sandwich geometry shown in Fig. 1(a).

2. Theory

Because the programmable standard uses only the constant-voltage steps at $V_0 = 0$ and $V_1 = \hbar\omega/2e$, where $f = \omega/2\pi$ is the rf bias frequency, optimum operation is obtained when the rf amplitude is adjusted to simultaneously maximize the current amplitudes,

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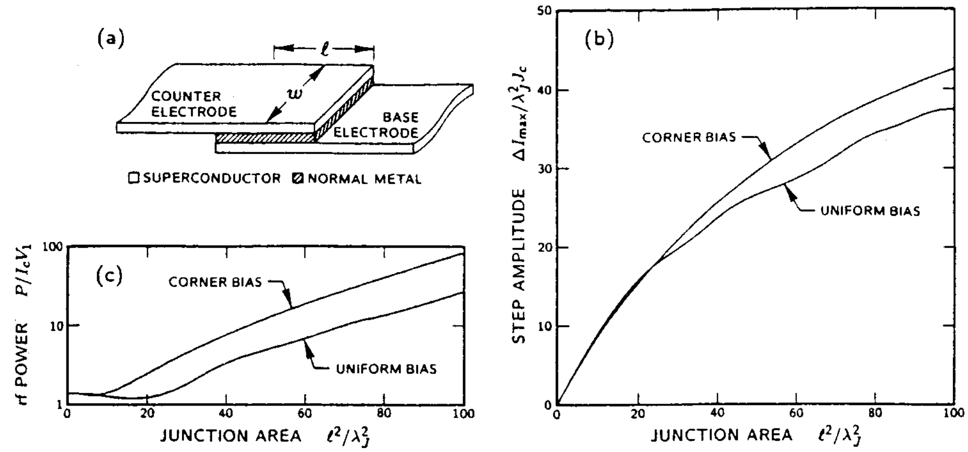

Figure 1. (a) Sandwich geometry of a metallic-barrier (SNS) junction of width w and length ℓ. (b) Maximum simultaneous current amplitude ΔI_{max} of the Shapiro steps of orders 0 and 1 as a function of area for a square SNS junction without a ground plane and $\Omega = 1$. (c) Microwave power P required to simultaneously maximize ΔI_0 and ΔI_1 as a function of area for a square SNS junction without a ground plane and $\Omega = 1$.

ΔI_0 and ΔI_1, of these two steps. The quantity of interest for voltage standards is thus $\Delta I_{\mathrm{max}} = \max[\min(\Delta I_0, \Delta I_1)]$, the simultaneous maximum of ΔI_0 and ΔI_1 over rf amplitude. For a rectangular SNS junction of width w, length ℓ, and critical current density J_c, the nominal critical current is $I_c = w\ell J_c$. However, the observed critical current I_c' is generally less than I_c if the dimensions exceed about 4 times the Josephson penetration depth $\lambda_J = \sqrt{\hbar/[2e\mu_0 J_c(d + 2\lambda)]}$, where d is the thickness of the metallic barrier and λ is the London penetration depth of the superconductor [3, 4]. Because step amplitudes typically scale as I_c', we can anticipate that ΔI_{max} will have a natural limit on the order of $16\lambda_J^2 J_c = 8\hbar/[e\mu_0(d + 2\lambda)]$, which is roughly 10 mA for typical values of $d + 2\lambda$.

The normalized drive frequency $\Omega = \hbar\omega/2eI_cR$, where R is the junction resistance, plays a crucial role in determining step amplitudes. For point junctions ($w, \ell \ll \lambda_J$), values of Ω less than 1 yield reduced step amplitudes. On the other hand, Clarke [5] has shown that for $\Omega > 1$ field penetration into the junction is limited roughly by the classical penetration depth δ_c of the metallic barrier at the drive frequency, rather than λ_J. Thus, reduced step amplitudes are also expected for large-area junctions with $\Omega > 1$, and the optimum Ω is expected to be near 1.

We have performed detailed simulations at $\Omega = 1$ for a square ($w = \ell$) SNS junction without a ground plane to determine the simultaneous maximum of ΔI_0 and ΔI_1. The dynamics of a large-area SNS junction are defined by the partial differential equation

$$\partial^2\phi/\partial x'^2 + \partial^2\phi/\partial y'^2 - \partial\phi/\partial t' - \sin\phi = 0, \tag{1}$$

where $\phi(x', y', t')$ is the junction phase, $x' = x/\lambda_J$ and $y' = y/\lambda_J$ are the normalized position coordinates, and $t' = t(2eI_cR/\hbar)$ is the normalized time. In our simulations, this equation is represented approximately by a two-dimensional array of zero-capacitance point junctions interconnected by inductors. The dc and rf bias currents enter the problem as boundary conditions on the array. Because the current flows primarily at the edges of the leads, the boundary conditions are reasonably approximated by injecting half of the bias current at each corner of the array. However, due to uncertainty in the degree to which current is confined to the corners, we also consider the case in which the bias current is distributed uniformly across the width of the leads. The case of uniform bias helps to set a bound on errors that might result from the corner-bias approximation.

The calculated $\Delta I_{\rm max}$ for a square SNS junction is plotted as a function of junction area in Fig. 1(b) for $\Omega = 1$. Results for the corner-bias and uniform-bias assumptions are roughly comparable, indicating that the simultaneous maximum of ΔI_0 and ΔI_1 is not sensitive to the bias-current distribution. Figure 1(b) shows that $\Delta I_{\rm max}$ is roughly $\ell^2 J_c$ for $\ell < 4\lambda_J$ and roughly $4\lambda_J \ell J_c$ for $\ell > 4\lambda_J$. Thus, the step amplitude $\Delta I_{\rm max}$ for square junctions does not saturate with increasing junction dimension but increases more slowly for $\ell > 4\lambda_J$. However, the rf power required to realize $\Delta I_{\rm max}$, plotted in Fig. 1(c), is roughly $I_c V_1$ for $\ell < 4\lambda_J$ but increases rapidly with junction area for $\ell > 4\lambda_J$. A junction with $w = \ell = 4\lambda_J$ thus defines a practical limit on step amplitude, namely $\Delta I_{\rm max} = 16\lambda_J^2 J_c$, or about 10 mA for typical values of $d + 2\lambda$. Steps of this size would make possible a voltage standard capable of supplying an output current of several milliamperes.

3. Experiment

Large-amplitude steps were explored experimentally in square Nb–PdAu–Nb junctions fabricated using a trilayer process. The current-voltage (I–V) characteristic of a series array of 400 SNS junctions is shown in Fig. 2, both in the absence of microwaves (a) and with 7.5 GHz radiation (b). In this array, the junction area was 2.5 μm by 2.5 μm and the metallic barrier was a 36-nm film of palladium-gold alloy (53% Pd and 47% Au by weight). From the measured critical current of $I_c' = 10.4$ mA, we estimate that

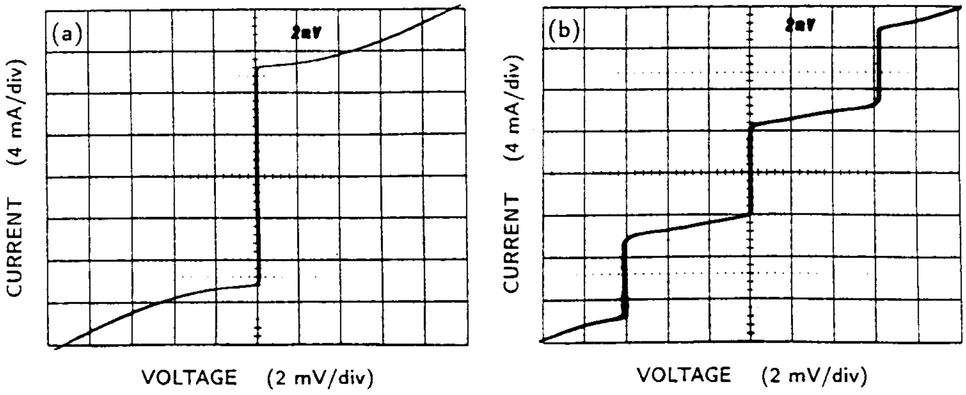

Figure 2. Current-voltage characteristics for a series array of 400 Nb–PdAu–Nb junctions at 4 K (a) in the absence of microwaves and (b) biased with 7.5 GHz radiation.

λ_J=0.87 μm, assuming $\lambda = 85$ nm for niobium. Thus, $\ell/\lambda_J = 2.9$, and the junction dimension is close to the optimum value for producing large-amplitude steps without excessive microwave power. Since the normal-state resistance is $R = 1.8$ mΩ, the reduced frequency at 7.5 GHz is approximately $\Omega = 0.8$, also close to ideal.

Figure 2(b) shows an I–V curve with the microwave power adjusted to simultaneously maximize ΔI_0 and ΔI_1. Under this bias condition, which is appropriate for a programmable voltage standard, the zero- and first-order steps have amplitudes of about 7 mA. When this amplitude is compared with steps of less than 50 μA typical of zero-bias arrays, the advantage of using SNS junctions becomes clear. In particular, the larger step amplitude allows currents of several milliamperes to be drawn from the SNS array. The additional stability provided by large-amplitude steps should also eliminate the need for the filters presently used to isolate zero-bias arrays from room-temperature noise. While such filters do not limit dc measurements, they can seriously degrade the accuracy of a waveform synthesized with a programmable array.

The I–V curves shown in Fig. 2 also provide good evidence for junction uniformity and microwave power uniformity in the SNS array. First, an accurate measurement of the voltage on the first Shapiro step agrees with that expected for a 400-junction array biased at 7.5 GHz. Second, if either the critical current or the rf bias were nonuniform, the corners between the vertical and resistive portions of the characteristic would appear rounded. The sharp corners apparent in Fig. 2(b) suggest that the uniformity required for building much larger arrays can be attained even with relatively small 2.5-μm junctions. Indeed, SNS sandwich junctions may prove to be the technology of choice for programmable Josephson voltage standards.

Acknowledgments

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