Subharmonic Shapiro steps in high- T_c Josephson junctions

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We studied the response of high- T_c biepitaxial grain boundary junctions to 100 GHz radiation in the presence of a magnetic field. Integer as well as subharmonic constant voltage steps are observed, even at one-fifth of the voltage separation between integer (Shapiro) steps. Our results indicate that this behavior is due to the synchronized motion of Josephson vortices along the junction. We show that this effect is directly related to the width of the junction, and not to an array of weaker regions in the barrier. © 1995 American Institute of Physics.

High frequency (HF) radiation, with a frequency f_{HF} , routinely induces constant voltage (Shapiro) steps (CVSs) in current-voltage characteristics (IVCs) of high- T_c Josephson junctions, at voltages which are integer multiples of $hf_{\text{HF}}/2e$.^{1,2} Frequently, however, also fractional CVSs appear²⁻⁵ at voltages $V_{n,m} = (n/m)(h/2e)f_{\text{HF}}$, with $n=0,1,2,\dots$ and $m=1,2,\dots$; m is the order of these steps. Such subharmonic CVSs are a signature of the geometry and Josephson properties of high- T_c junctions, as they are for other devices.^{3,6-9} In this letter we show that the observed behavior is a result of the junction width W , which is measured relative to the Josephson screening length $\lambda_J \approx [h/8\pi\mu_0 e j_c \lambda_L]^{1/2}$, with j_c the junction's critical current density and λ_L the London penetration depth. For small screening ($W < \lambda_J$) the device is a point object, whose dynamics are described by the resistively shunted junction (RSJ) model. If the magnetic field at the edges of a wide junction ($W > \lambda_J$) exceeds a critical value, Josephson vortices enter the junction, which then determine its dynamics.^{7,10} Synchronization of the motion of these vortices causes the subharmonic CVSs in wide high- T_c junctions.

In this study we used biepitaxial $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ grain boundary junctions (GBJs). The fabrication process and electrical characteristics were described previously.¹¹ A number of 17 junctions, 5–20 μm wide, were investigated. At 20 K, the temperature at which all the presented results were obtained, the junctions have an average $j_c \approx 20 \text{ kA/cm}^2$, resistivity $\rho_n \approx 3 \times 10^{-8} \Omega \text{ cm}^2$, and characteristic voltage $V_c = j_c \cdot \rho_n \approx 0.5 \text{ mV}$. The average deviation from these values is about 50%, indicating that junction properties like the barrier thickness are very inhomogeneous. IVCs of small junctions are RSJ-like. Those of wide ones show deviations like excess currents and bumps, although a sharp voltage onset and rapid approach toward a constant slope remain present. Such deviations were also found by others for wide junctions.¹²

Millimeter-wave radiation ($f_{\text{HF}} = 100 \text{ GHz}$) and a perpendicular magnetic field H_{ext} (up to 150 Gauss) were applied to the junctions simultaneously.² Depending on H_{ext} and the HF power P_{HF} , subharmonic CVSs appeared in the IVC of most junctions. Figure 1 shows two examples. For each case H_{ext} and P_{HF} were tuned to obtain the highest

order subharmonic step. Curve (a) represents a 5 μm wide junction showing only integer and half steps. Similar IVCs were found by Early *et al.*⁴ and Pauza *et al.*⁵ By contrast, we also found higher order subharmonic steps: curve (b) shows an IVC for a 15 μm wide junction with steps up to $m=5$.

The results in Fig. 1 suggest that the highest order subharmonic step m_{max} increases with increasing junction width. This is confirmed in the inset to Fig. 1, which for all junctions shows m_{max} versus W , normalized to their respective λ_J value, using $\lambda_L \approx 150 \text{ nm}$.¹² A factor π is included for reasons to be discussed. Good scaling is found between this HF characteristic and the normalized widths, despite the large inhomogeneities. In order to be independent of random junction variations, we used a focused ion beam etcher (FIB, using 25 keV Ga^+ ions, 50 nm spot size FWHM) to narrow a 20 μm wide junction (* in Fig. 1) to 12 μm and in a second step to 3 μm . In the narrowed junction ($\diamond$) m_{max} has become smaller too. For the 3 μm wide junction, all subharmonics, just as the described peculiarities in the IVC, vanished.

The order of observed subharmonic steps varies with H_{ext} from 1 to m_{max} . For the junction of Fig. 1(b), Fig. 2 shows IVCs for various H_{ext} values. Clearly this device, with $m_{\text{max}} = 5$, can be tuned to states with different subharmonic

FIG. 1. IVCs of (a) a 5 μm and (b) a 15 μm wide junction for optimized H_{ext} and P_{HF} (see text). Indices m,n label the CVSs. The inset shows the maximum order subharmonic step m_{max} vs the normalized junction width $W/\pi\lambda_J$ for all junctions.

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FIG. 2. IVCs for a 15 μm wide junction with $m_{\text{max}}=5$ for various values of H_{ext} .

steps, having m 's of only 1 [Fig. 2(a)], 1,2 [Fig. 2(b)], 1–3 [Fig. 2(c)], 1–4 [Fig. 2(d)], or 1–5 [Fig. 2(e)]. These states appear with the period of $I_c(H_{\text{ext}})$. For the junction of Fig. 1(a), with $m_{\text{max}}=2$, Fig. 3 shows the dependence on H_{ext} of I_c and the maximum amplitudes of the $n/m=1/2$ and $n/m=1$ steps. Half steps are maximal when I_c and the integer steps are minimal, in agreement with results of Early *et al.*⁴

The modulation of the steps with P_{HF} depends on H_{ext} in a complicated way. Figure 4 shows results for the junction of Fig. 1(a), as a function of $I_{\text{HF}}=KP_{\text{HF}}^{1/2}$, for no half steps [Fig. 4(a)] and maximum half steps [Fig. 4(b)]. Solid lines are solutions of the RSJ model for the zero voltage step and the first two integer steps, which are fitted to the measurements using the parameters $\Omega=(h/2e)f_{\text{HF}}/V_c$ and K . In Fig. 4(a) we find $\Omega_{\text{fit}}^a \approx \Omega_{\text{exp}}^a$, so model and measurements agree nicely. This agreement is lost in Fig. 4(b): a good fit for $I_0(I_{\text{HF}})$ is found for $\Omega_{\text{fit}}^b=0.35$, but $\Omega_{\text{exp}}^b=0.58$. Surprisingly, Ω_{fit}^b fits the calculated first two integer steps to the measured $n/m=1/2$ and $n/m=1$ steps, respectively. All junctions behave in this way if the half steps are maximal.

To clarify the origin of subharmonic CVSs in our GBJs, our results are compared with those on other Josephson devices showing similar steps. Basically, these are caused either by harmonics of the Josephson oscillation, or by vortex motion.

Phase locking of the m th harmonic of the Josephson os-

FIG. 3. Dependence of the maximum amplitude of the CVSs on H_{ext} for a 5 μm wide junction ($m_{\text{max}}=2$).

FIG. 4. Modulation of CVSs ($\square$) with I_{HF} for a 5 μm wide junction ($m_{\text{max}}=2$) for two H_{ext} values, for which (a) no half steps and (b) maximum half steps appear. Data and I_{HF} are normalized to the respective $I_c^{a,b}$ values. Solid lines are solutions of the RSJ model for $I_0(I_{\text{HF}})/I_c$ and the first two integer steps using the indicated $\Omega_{\text{fit}}^{a,b}$.

cillation with the n th harmonic of f_{HF} leads to CVSs at voltages $V_{n,m}$. This effect is found for junctions with a nonsinusoidal current-phase relation, like long microbridges,⁶ or with a reactive element nearby.³ The scaling of m_{max} with $W/\pi\lambda_J$, and the modulation of the steps with H_{ext} and P_{HF} , disagree with these models. Our results are better explained by the synchronized motion of Josephson vortices.

In two-dimensional (2D) junction arrays, with N junctions in the transport current direction, the synchronized motion of a vortex superlattice causes fractional giant CVSs at voltages $NV_{n,m}$. This superlattice is induced by a perpendicular magnetic field corresponding to k/m flux quanta per array unit cell (with k, m integers).⁹ The smallest array is a parallel connection of two junctions, or dc SQUID (superconducting quantum interference device). In this device half CVSs appear due to a flip-flop between the SQUID's fluxoid states.⁸ Regarding the irregular barrier in GBJs as a network of strong and weak zones, Early *et al.* suggested a parallel SQUID array to be a suitable model to account for half CVSs.⁴ The influence of H_{ext} and P_{HF} on the steps indeed resembles properties of arrays. For $H_{\text{ext}}=0$, for instance, the giant integer CVSs modulate with P_{HF} according to the RSJ model, while for a field with $k/m=1/2$ minima (maxima) of $(n/2)$ th steps appear, where the RSJ model predicts minima (maxima) for the n th integer step.⁹ Our results contradict this model, however. For a SQUID $m_{\text{max}}=2$,¹³ but since the number of fluxoid states increases in a SQUID array m_{max} does too. As j_c and V_c scatter in our GBJs, the number of weak and strong zones is unpredictable, so the scaling shown in Fig. 1 between m_{max} and $W/\pi\lambda_J$ is unexpected.

Our results are best explained by the synchronized motion of Josephson vortices along a wide junction. Only irregularities with a size $\geq \lambda_J$ then affect the junction dynamics.¹ Smaller defects, that are amply present in GBJs, are not seen by the vortices, so the “array” in the barrier can be disregarded. An illustrative image for periodic vortex motion is the motion over the junction of an infinite vortex array. The unit cell of this array is $\pi\lambda_J$, being about the size of an isolated vortex,¹ while the period P (in units $\pi\lambda_J$) is fixed by H_{ext} . This image compares to that for junction arrays. The difference lies in the potential through which the

vortices move. For arrays, potential maxima lie on the junctions, minima on the holes. For wide junctions, maxima lie on the junction edges, while the interior of the junction is the potential minimum. Our junctions lie in between the small and wide limit, so the maximum number of vortices $M = W/\pi\lambda_J$ is small.⁷ For a junction with $M=3$ the largest possible array period thus is $P=4$: the junction alternately screens the magnetic field or contains one vortex.

Phase locking of vortex motion to a HF signal causes CVSs at voltages $V_{n,m}$,⁷ when n vortices pass in m HF cycles. However, the order of observed subharmonic steps is limited by P , as the distance of a vortex from the edge must always be larger than $\pi\lambda_J/2$. Thus the array must move at least $\pi\lambda_J$ per HF cycle, so that $m_{\max}=P=M+1$. If the array with $M=3$, $P=4$ moves $\pi\lambda_J$ each HF cycle an $m=4$ step appears. In the inset to Fig. 1 this prediction is shown as a solid line, which agrees well with the results. For $M=1$ $m_{\max}=2$ so our model is identical to the flip-flop between fluxoid states in SQUIDs. Depending on H_{ext} a junction with $M=4$ contains 0, 1, 2, 3, or 4 vortices. This leads to arrays with $1 \leq P \leq 5$ and the corresponding subharmonic steps, as observed in Fig. 2. The resemblance between wide junctions and junction arrays also explains the modulation of CVSs with H_{ext} and I_{HF} in Figs. 3 and 4.⁹

In conclusion, simultaneous exposure of biepitaxial GBJs to 100 GHz irradiation and a magnetic field was found to cause the appearance of subharmonic CVSs. We attribute the observed behavior to the motion of Josephson vortices along the junctions being phase locked to the HF signal. In

essence this model identifies the junctions as a parallel array of a few SQUIDs, which is *not* related to the number of shorts in the barrier but to the number of vortices that are present in the junction. The resemblance with junction arrays was successfully used to give a qualitative interpretation of our measurements.

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