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Parallel array of YBa2Cu3O7–δ superconducting Josephson vortex-flow transistors with high current gains
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High temperature superconductor Josephson vortex-flow transistors (JVFTs) are the most promising candidates for high-frequency amplifying devices in all-superconducting microwave circuits.\textsuperscript{1,2} There are two types of JVFTs: ones based on a single long Josephson junction (JJ)\textsuperscript{3} or JVFTs based on arrays of JJs.\textsuperscript{4–7} A high performance JVFT for practical applications should have a high current gain, $g = \partial I_c / \partial I_{ctrl}$ (where $I_c$ is the device critical current and $I_{ctrl}$ is the control-gate current), a large dynamic range (the range of $I_{ctrl}$ over which a high $g$ can be achieved), small vortex transit times to allow high frequency operation and a relatively large transresistance, $r_m = \partial V / \partial I_{ctrl}$. Several JVFT designs have been proposed so far which differ in (i) current bias distribution (symmetric overlap\textsuperscript{1,3} or asymmetric in-line\textsuperscript{5–7}), or (ii) gate line geometry (different gate design\textsuperscript{4} or different gate line relative orientation with respect to the junctions\textsuperscript{6,7}). It has been shown\textsuperscript{1,3} that discrete JVFTs with an asymmetric current bias distribution have much larger current gains than discrete JVFTs with a symmetric one. This is due to self-field effects that translate into a highly asymmetric $I_c(I_{ctrl})$ pattern. However, one significant drawback is that they are also characterized by relatively large vortex transit times and a small dynamic range in comparison to their symmetrical counterparts.\textsuperscript{8} In this paper we propose a discrete JVFT based on a parallel array of 440 YBa$_2$Cu$_3$O$_{7-\delta}$ bicrystal grain boundary Josephson junctions. The array’s critical current $I_c$ was measured as a function of the control current $I_{ctrl}$ through a control line that is inductively coupled to the array. The device has a highly asymmetric $I_c(I_{ctrl})$ curve with several regions where a switching behaviour is observed characterized by a maximum current gain $g_{max} = \partial I_c / \partial I_{ctrl}$ of 19 and a significant dynamic range of 20 $\mu$A at 77 K. In the range 4.7–92 K $g_{max}$ versus temperature is non-monotonic with a maximum recorded at 77 K. © 2013 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4819461]
within the array by varying the value of $\beta_L$ monotonically within each set of 20 JJs by about $\pm 15\%$ around its average. We chose a logarithmic dependence for $\beta_L$ because it introduces a smaller degree of asymmetry than a linear dependence. The bias current, $I$, is applied symmetrically via the central top and bottom electrodes. The control current is fed through a control line (dotted line in Fig. 1), which is electrically decoupled from, and inductively coupled to, the array. We have fabricated two such devices and both showed a similar behaviour. In particular, the devices show a similar robust operation with or without a magnetically and electrically shielded environment which demonstrates the practicality of the design.

Families of dc current-voltage (IV) characteristics were measured by a 4 point-contact method at various temperatures between 4.7 K and 92 K and for different values of the control current $I_{ctrl}$ in the range $(-8\, \text{mA}, \, 8\, \text{mA})$. $I_{ctrl}$ was changed in small steps of 15 $\mu\text{A}$. A family of 35 consecutive IVs measured at 77 K are plotted in Fig. 2. A maximum voltage modulation of 14 $\mu\text{V}$, due to a change in $I_{ctrl}$ between the first IV (IV number 1 on Fig. 2) and the last IV (IV number 4) in this particular family, was recorded at a fixed current bias of 1 mA. In blue are the two IV’s numbered 2 and 3 for $I_{ctrl}$ range where a switching behaviour is observed: a small current of 15 $\mu\text{A}$ applied to the JJFT’s gate increases the JJFT’s drain-source current by 280 $\mu\text{A}$. That translates into a Josephson critical current density $J_c$ and consequently the self-field effects of the supercurrent become important. Since the inductance values of individual loops change monotonically within each set of 19 consecutive loops, due to differences in their lengths, a significant asymmetry appears between the left and the right half of the device as far as the self-induced flux in the loops is concerned. As a result, the bias current $I$ produces a net inhomogeneous magnetic flux along the array that is proportional to $I$. The additional flux due to the self-field effects causes an increased (positive feedback) and a reduced slope (negative feedback) of the increasing and decreasing branches, respectively, of the $I_c(I_{ctrl})$ curve measured at 89 K. This is because the same change of the applied flux $\Phi_0$ (produced by $I_{ctrl}$) results in larger or smaller changes of the critical current of the device. An asymmetric $I_c(I_{ctrl})$ curve is therefore expected for this device at $T < 89\, \text{K}$ along with the associated high current gains. The asymmetry of $I_c(I_{ctrl})$ as well as $g_{\text{max}}$ are expected to increase rapidly with decreasing temperature as self-field effects (that are proportional to $\beta_L$) are enhanced according to the temperature dependence of $J_c$. Such a behaviour is indeed observed in a set

![Parallel array of 22 x 20 JJ](image)

**FIG. 1.** Optical micrograph of the JJFT made of a parallel array of 22 identical sets of 20 JJ. Shown is a small central part of the array consisting of 4 superconducting loops of identical width (3 $\mu\text{m}$) and variable length (logarithmically decreasing from 18 $\mu\text{m}$ to 13 $\mu\text{m}$). This geometry introduces an asymmetry with respect to the direction of the current bias $I$ and consequently an inhomogeneous net magnetic flux proportional to $I$ is produced along the array.

**FIG. 2.** A set of 35 consecutive current-voltage IV characteristics recorded at 77 K for various values of the control current $I_{ctrl}$ around 1.2 mA. $I_{ctrl}$ is changed in steps of 15 $\mu\text{A}$. In red are the two IV’s numbered 1 and 4 for the extreme values of $I_{ctrl}$. In blue are the two IV’s numbered 2 and 3 for the $I_{ctrl}$ range where a switching behaviour is observed with current gains as high as 19. Inset shows a very unusual maximum current gain $g_{\text{max}}(T)$ dependence in the range (4.7, 89) K with a maximum recorded value at 77 K.
of measurements taken at 89 K, 84 K, 81 K, and 77 K (see Figs. 4(a) and 4(b)) where the degree of $I_c(I_{ctrl})$ asymmetry and $g_{max}$ both gradually increase as we decrease $T$. A similar rapid transition with increasing $\mu_1$ (decreasing temperature) from a symmetric $I_c(I_{ctrl})$ to an asymmetric one was predicted to occur in discrete JVFTs with an asymmetric current bias distribution.\textsuperscript{1,7,8} Considering the increase in $I_c$ due to a change in temperature from 89 K to 77 K an average value for $\mu_1$ of 1.9 can be estimated at 77 K which is close to the designed value of 1.5. In contrast to $I_c(I_{ctrl})$ curves, $V(I_{ctrl})$ curves are almost symmetric at all temperatures.

A switching behaviour is observed at 77 K with current gains as high as $g = 19$ and a corresponding dynamic range of $\Delta I_{ctrl} > 20 \mu A$ for positive voltages (see Fig. 4(a)) and $g = 10$ with a corresponding $\Delta I_{ctrl} > 15 \mu A$ for negative voltages (Fig. 4(b)). A similar behaviour is observed at 81 K as well, with slightly smaller values for $g$ and $\Delta I_{ctrl}$ associated with it. Interestingly, a switching behaviour that is due to strong self-field effects with very high values of $g$ associated with it have been predicted theoretically\textsuperscript{4} for JVFTs with an asymmetric bias current distribution.\textsuperscript{1,8} However, it has never been observed experimentally. In our case the switching behaviour has a different nature, as explained below. First, it should be noted that flux-flow resonance modes occur in our system that are due to the motion of a chain of vortices through the discrete JJ array, accompanied by an emission of small amplitude linear waves that propagate along the array. When the vortex spacing is commensurate with the wavelength of the emitted waves flux-flow resonances are produced on the family of IV's\textsuperscript{11,12} Two such resonances, which are tunable in a magnetic field (i.e., their voltage location strongly depends on the applied magnetic field via $I_{ctrl}$), are clearly visible in Fig. 2. A detailed investigation of these resonances will be published elsewhere.\textsuperscript{13} A breakdown of these flux-flow resonance modes occurs within a very narrow range of $I_{ctrl}$ (that corresponds to the two blue IV's numbered 2 and 3 on Fig. 2). This triggers a sharp transition involving several hundred JJs from a state where the array’s $I_c$ has a value close to a minima—corresponding to destructive interference of individual $(I_c)_i$ (see blue IV numbered 2 on Fig. 2)—to a state where the array’s $I_c$ is close to its maxima—corresponding to constructive interference of individual $(I_c)_i$ (see blue IV numbered 3 on Fig. 2).

It is important to note that at lower temperatures (4.7 K, 10 K, 30 K, and 57.5 K) $g_{max}$ values are significantly smaller (see inset of Fig. 2). Although never observed experimentally such a non-monotonic $g(T)$ dependence characterized by a maximum has been predicted by numerical simulations performed for discrete JVFT’s with an asymmetric current bias distribution.\textsuperscript{5} In our case the physics behind this can be understood as follows: decreasing the temperature leads to a decrease in the losses experienced by moving fluxons (i.e., smaller damping) accompanied by an increased discreteness of the array (the discreteness parameter is $(\beta_L)^{1/2}$). At some threshold temperature, $T_{th}$, numerical simulations show that flux-flow resonances are completely suppressed and a transition to a chaotic regime occurs.\textsuperscript{12} Consequently, in our case for temperature below $T_{th}$ (which appears to be around 77 K)
the switching behaviour and the high gains associated with the flux-flow resonances both vanish.

We have developed a JVFT prototype based on arrays of $JJ$ with an asymmetric loop configuration and demonstrated its operation in a wide temperature range 4.7–92 K. The device shows very promising performance in the areas of current gain and dynamic range. For some applications a primary concern might be the low impedance, $r_m$, of these devices. This issue can be solved by using an alternative to $JJ$ bicrystal technology (e.g., a ramp-type $JJ$) for the implementation of our concept. The device operates in both magnetically and electrically unshielded environments and at 77 K demonstrating its potential for practical devices. The design approach reported here shows great promise as a route to realizing high performance supercomputing amplifiers using JVFTs.

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9. The films were deposited by Theva GmbH.