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Parallel array of $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ superconducting Josephson vortex-flow transistors with high current gains

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We have developed a Josephson vortex-flow transistor based on a parallel array of 440 $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ 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.

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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, $I_b$, 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 ($-8$ mA, $8$ mA). $I_{ctrl}$ was changed in small steps of $15 \mu$A. A family of 35 consecutive IVs measured at 77 K are plotted in Fig. 2. A maximum voltage modulation of $14\mu$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 $I$ applied to the JVFT’s gate increases the IV’s 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 $15 \mu$A. In red are the two IV’s numbered 1 and 4 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 $g_{max}(T)$ dependence in the range (4.7, 89) K with a maximum recorded value at 77 K.

At temperatures close to $T_c$, we are in the low-inductance limit in which $\beta_L$ are negligibly small and the magnetic fields of the bias current $I_b$ can be neglected. Therefore, the magnetic field dependence of the array critical current, $I_{cJ}$, is unaffected by $I_b$ and should have a symmetric and periodic pattern consisting of a series of maxima similar to a diffraction pattern of an optical grating consisting of multiple slits. The periodicity in $I_{ctrl}$ corresponds to one additional flux quantum $\Phi_0$ in each loop. This is confirmed by the experiments as shown in Fig. 3 where $I(I_{ctrl})$ for 5 different voltage criteria between $-0.2 \mu$V and $-1 \mu$V measured at 89 K show a symmetric and periodic pattern with a periodicity of about 2 mA. We performed numerical simulations based on a model developed earlier $^{10}$ in the limit of small $\beta_L$ and from the modulation of $I_b$ with $I_{ctrl}$ we estimate an average value for $\beta_L$ of 0.3 at 89 K. As the temperature is decreased $\beta_L$ can no longer be neglected (due to an increase in $I_{ctrl}$) and consequently the self-field effects of the supercurrents 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 $I(I_{ctrl})$ curve measured at 89 K. This is because the same change of the applied flux $\Phi_{ctrl}$ (produced by $I_{ctrl}$) results in larger or smaller changes of the critical current of the device. An asymmetric $I(I_{ctrl})$ curve is therefore expected for this device at $T < 89$ K along with the associated high current gains. The asymmetry of $I(I_{ctrl})$ as well as $g_{max}$ 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 $I_{cJ}$. Such a behaviour is indeed observed in a set

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**Fig. 1.** Optical micrograph of the JVFT made of a parallel array of 22 identical sets of 20 JJ. Shown is a small central part of the array consisting of 4 sets of 20 JJ. Within each set all 20 JJ are 3 µm wide and are connected via superconducting loops of identical width (3 µm) and variable length (logarithmically decreasing from 18 µm to 13 µm). This geometry introduces an asymmetry with respect to the direction of the current bias $I_b$ and consequently an inhomogeneous net magnetic flux proportional to $I_b$ 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 $15 \mu$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 $g_{max}(T)$ dependence in the range (4.7, 89) K with a maximum recorded value at 77 K.

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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 $\beta_L$ (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.$^{1,7,8}$ Considering the increase in $I_c$ due to a change in temperature from 89 K to 77 K an average value for $\beta_L$ 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$^{1}$ for JVFTs with an asymmetric bias current distribution.$^{1,8}$ 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 $IV's$. 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.$^{12}$ 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 $JJ's$ from a state where the array’s $I_c$ has a value close to a minima—corresponding to destructive interference of individual $I_c(J)$ (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 $I_c(J)$ (see the 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.$^7$ 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.$^{12}$ 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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