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Chesca, Boris, Daniel John, Matthew Kemp, Jeffrey Brown, and Christopher Mellor. 2019. "Parallel Array of $\text{Yba}_2\text{cu}_3\text{o}_7-\delta$ Superconducting Josephson Vortex-flow Transistors with High Current Gains". figshare. <https://hdl.handle.net/2134/13056>.

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Citation: [Appl. Phys. Lett.](#) **103**, 092601 (2013); doi: 10.1063/1.4819461

View online: <http://dx.doi.org/10.1063/1.4819461>

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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

Boris Chesca,¹ Daniel John,¹ Matthew Kemp,¹ Jeffrey Brown,¹ and Christopher Mellor²

¹Department of Physics, Loughborough University, Loughborough, United Kingdom

²School of Physics and Astronomy, Nottingham University, Nottingham, United Kingdom

(Received 21 June 2013; accepted 14 August 2013; published online 28 August 2013)

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 μA 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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High temperature superconductor Josephson vortex-flow transistors (JVFTs) are the most promising candidates for high-frequency amplifying devices in all-superconducting microwave circuits.^{1,2} There are two types of JVFTs: ones that are based on a single long Josephson junction (JJ)^{3,4} or JVFTs based on arrays of JJs .^{5–7} 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^{1,3} or asymmetric in-line^{5–7}), or (ii) gate line geometry (different gate design⁴ or different gate line relative orientation with respect to the junctions⁶). It has been shown^{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.⁸ In this paper we propose a discrete JVFT based on a parallel array of 440 $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ bicrystal grain boundary JJ that combines beneficial aspects of several previous designs. On the one hand, it has a symmetric bias configuration to ensure a large dynamic range, as well as, small vortex transit times; on the other hand it has a certain degree of inductive asymmetry implemented via an asymmetric loop configuration within the array. This asymmetry ensures the bias current produces a net inhomogeneous magnetic field along the array through self-field effects that result in a highly asymmetric $I_c(I_{ctrl})$ curve with high current gains. Of particular interest are JVFTs operating at 77 K due to their low-cost cooling procedures and practicality. There have been several reports of JVFTs with current gains g as high as 6 at 30 K⁴ or 5.5 at 50 K,⁶ or 14 at 70 K,⁵ however, in all these cases $g(T)$ rapidly and monotonically decreases with temperature as it approaches 77 K. Thus, the

highest current gains reported so far at 77 K were achieved with discrete JVFTs having an asymmetric in-line bias distribution (maximum reported values were $g = 3.5^7$). Our discrete JVFT shows current gains as high as 19, a significant dynamic range of more than 20 μA at 77 K, and an unusual non-monotonic $g(T)$ dependence in the range (4.7–92) K with a maximum recorded value at 77 K.

The JVFTs were fabricated by depositing high quality epitaxial, 100 nm thick c -axis oriented $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ (YBCO) films on $10 \times 10 \text{ mm}^2$, 24° symmetric [001] tilt, SrTiO_3 bicrystals by pulsed laser deposition.⁹ A 200 nm thick Au layer was deposited *in situ* on top of the YBCO film to facilitate fabrication of high quality electrical contacts for electric transport measurements. The films with a critical temperature, T_c , of 92 K were subsequently patterned by optical lithography and etched by an Ar ion beam to form a parallel array of 440 JJ . The array consists of 22 identical sets of 20 JJ each. All 440 JJ are 3 μm wide. The junctions are separated by superconducting loops of identical width (3 μm) but variable length. Thus, within each set of 20 JJ the length of the loops varies logarithmically from 13 μm to 8 μm . Consequently, the screening parameter $\beta_{Li} = 2\pi L_i I_{cJ} / \Phi_0$ is also changing monotonically within each set of 19 superconducting loops. Here Φ_0 is the flux quantum, I_{cJ} is the maximum Josephson critical current of each junction and L_i is the inductance of the superconducting loop between JJ_i and JJ_{i+1} , with $i = 1, 2, \dots, 19$. An optical micrograph of a small part of such a JVFT (containing 4 such sets of 20 JJ each) is shown in Fig. 1. We designed our JJ array following several considerations as explained below. Previous investigations^{6,7} showed that for symmetric discrete JVTF with $N = 9, 10$ and a constant value of β_L throughout the array $g(\beta_L)$ increases monotonically with β_L and saturates for β_L values larger than about 7. From numerical simulations of $I_c(I_{ctrl})$ versus β_L performed for asymmetric discrete JVFT¹ it is found that $g(\beta_L)$ saturates much faster, i.e., for β_L values larger than about 1.5 for $N = 10$. Consequently, we designed our JJ array to have an average β_L of about 1.5 at 77 K. To ensure a highly asymmetric $I_c(I_{ctrl})$ pattern with the high g values associated with it, we also implemented an asymmetric loop configuration

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 and consequently an inhomogeneous net magnetic flux proportional to I is produced along the array.

within the array by varying the value of β_L monotonically within each set of 20 JJs by about $\pm 15\%$ around its average. We chose a logarithmic dependence for β_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 mA, 8 mA). I_{ctrl} was changed in small steps of 15 μA . A family of 35 consecutive *IV*s measured at 77 K are plotted in Fig. 2. A maximum voltage modulation of 14 μV , 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 μA applied to the JVFT's gate increases the JVFT's drain-source current by 280 μA . That translates into current gains g as high as 19. From such families of *IV*'s scanned over I_{ctrl} , $I_c(I_{ctrl})$ dependencies could be constructed for various voltage criteria (see Figs. 3 and 4) and a maximum value $g_{max} = \max(\partial I_c / \partial I_{ctrl})$ for the current gain can be calculated. Remarkably, in contrast to previous reports on other types of discrete JVFTs,¹⁻⁷ $g_{max}(T)$ is highly non-monotonic with a maximum recorded value at 77 K (see inset of Fig. 2). From the measured *IV*s in a magnetically shielded environment for each individual junction, I_{cJ} of about 3 μA and $I_{cJ}R_N$ product of about 50 μV were calculated at 77 K (where R_N is the junction's normal resistance). That translates into a Josephson critical current density J_c of about $1 \times 10^3 \text{ A/cm}^2$. As expected by using JJ bicrystal technology for the implementation of our concept only relatively modest values for its transresistance, r_m , of about 0.04 Ω at 77 K were achieved.

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 μA . 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.

At temperatures close to T_c we are in the low-inductance limit in which β_{Li} are negligibly small and the magnetic fields of the bias current I can be neglected. Therefore, the magnetic field dependence of the array critical current, I_c , is unaffected by I 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.¹⁰ The periodicity in I_{ctrl} corresponds to one additional flux quantum Φ_0 in each loop. This is confirmed by the experiments as shown in Fig. 3 where $I_c(I_{ctrl})$ for 5 different voltage criteria between −0.2 μV and −1 μV 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 earlier¹⁰ in the limit of small β_L and from the modulation of I_c with I_{ctrl} we estimate an average value for β_L of 0.3 at 89 K. As the temperature is decreased β_{Li} can no longer be neglected (due to an increase in I_{cJ}) 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 $I_c(I_{ctrl})$ curve measured at 89 K. This is because the same change of the applied flux Φ_{ctrl} (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_{max} are expected to increase rapidly with decreasing temperature as self-field effects (that are proportional to β_{Li}) are enhanced according to the temperature dependence of I_{cJ} . Such a behaviour is indeed observed in a set

FIG. 3. $I_c(I_{ctrl})$ at 89 K for 5 different voltage criteria between $(-1, -0.2)$ μV showing a symmetric and periodic pattern with a periodicity of about 2 mA.

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 β_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 β_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 $\Delta I_{ctrl} > 20 \mu\text{A}$ for positive voltages (see Fig. 4(a)) and $g = 10$ with a corresponding $\Delta I_{ctrl} > 15 \mu\text{A}$ for negative voltages (Fig. 4(b)). A similar behaviour is observed at 81 K as well, with slightly smaller values for g and ΔI_{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 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.^{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.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 JJ s from a state where the array's I_c has a value close to a minima—corresponding to destructive interference of individual $(I_{cJ})_i$

FIG. 4. (a) $I_c(I_{ctrl})$ at 77 K for 7 different voltage criteria between $(0.1, 0.7)$ μV showing a highly asymmetrical pattern. A switching behaviour is clearly visible at about $I_{ctrl} = 1.2 \text{ mA}$ with current gains as high as 19 and a dynamic range of more than $20 \mu\text{A}$. (b) Similar to (a) except for voltage criteria between $(-0.7, -0.1)$ μV . Again a switching behaviour is clearly visible at about $I_{ctrl} = -0.8 \text{ mA}$ with current gains as high as 10 and a dynamic range of more than $15 \mu\text{A}$.

(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 $(I_{cJ})_i$ (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.

The authors would like to thank Dominic Walliman and Jas Chauhan for their technical support.

- ¹R. Gross, R. Gerdemann, L. Alff, T. Bauch, A. Beck, O. M. Froehlich, D. Koelle, and A. Marx, *Appl. Supercond.* **3**, 443 (1995).
- ²J. Mannhart, *Supercond. Sci. Technol.* **9**, 49 (1996).
- ³Y. M. Zhang, D. Winkler, P. A. Nilsson, and T. Claeson, *Appl. Phys. Lett.* **64**, 1153 (1994).
- ⁴S. J. Berkowitz, Y. M. Zhang, W. H. Mallison, K. Char, E. Terzioglu, and M. R. Beasley, *Appl. Phys. Lett.* **69**, 3257 (1996).
- ⁵R. Gerdemann, T. Bauch, O. M. Froehlich, L. Alff, A. Beck, D. Koelle, and R. Gross, *Appl. Phys. Lett.* **67**, 1010 (1995).
- ⁶J. Schuler, S. Weiss, T. Bauch, A. Marx, D. Koelle, and R. Gross, *Appl. Phys. Lett.* **78**, 1095 (2001).
- ⁷T. Bauch, S. Weis, H. Haensel, A. Marx, D. Koelle, and R. Gross, *IEEE Trans. Appl. Supercond.* **7**, 3605 (1997).
- ⁸B. A. Davidson, V. Granata, E. Sarnelli, and S. Pagano, *Supercond. Sci. Technol.* **12**, 970 (1999).
- ⁹The films were deposited by Theva GmbH.
- ¹⁰J. H. Miller, G. H. Gunaratne, J. Huang, and T. D. Golding, *Appl. Phys. Lett.* **59**, 3330 (1991).
- ¹¹H. S. J. van der Zant, T. P. Orlando, S. Watanabe, and S. H. Strogatz, *Phys. Rev. Lett.* **74**, 174 (1995).
- ¹²A. V. Ustinov, M. Cirillo, B. H. Larson, V. A. Oboznov, P. Carrelli, and G. Rotoli, *Phys. Rev. B* **51**, 3081 (1995).
- ¹³B. Chesca, D. John, and C. J. Mellor, “Amplification of electromagnetic waves excited by a chain of propagating vortices in YBCO Josephson-junction arrays” (unpublished).