All-high-$T_c$ superconductor rapid-single-flux-quantum circuit operating at $\sim 30$ K

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We have implemented a simple circuit of the rapid single-flux-quantum (RSFQ) logic family using a single-layer YBa$_2$Cu$_3$O$_{7-x}$ thin-film structure with 14 in-plane Josephson junctions formed by direct electron beam writing. The circuit includes two dc/SFQ converters, two Josephson transmission lines, a complete RS SFQ flip-flop, and an SFQ/dc converter (readout SQUID). Low-frequency testing has shown that the dc-current-biased circuit operates correctly and reliably at $T \sim 30$ K, a few degrees below the effective critical temperature of the junctions. Prospects for a further increase of the operation temperature and implementation of more complex RSFQ circuits are discussed in brief. © 1995 American Institute of Physics.

The past few years have witnessed rapid development of superconductor digital circuits of the rapid single-flux-quantum (RSFQ) logic family. These circuits, using overdamped Josephson junctions as active elements, store binary information in the form of single quanta of magnetic flux, $\Phi_0/h = 2 e \times 10^{-15}$ Wb, while transferring and processing it in the form of picosecond SFQ pulses with the quantized area $f V(t) dt = \Phi_0 \approx 2$ mV×ps (for reviews, see Ref. 1). The main advantage of this new digital technology is its unparalleled speed (fundamentally limited only by the superconductor energy gap) combined with very low power consumption and dc power supply. The main problem preventing practical application of the RSFQ circuits is the necessity of deep refrigeration.

This drawback could be substantially alleviated by using high-$T_c$ superconductors that may allow operation of RSFQ circuits at liquid nitrogen temperatures.1–3 Most Josephson junctions of high-$T_c$ superconductors are intrinsically overdamped (and as a result have nonhysteretic dc $I$–$V$ curves), making implementation of RSFQ circuits very natural. That is why considerable efforts to produce high-$T_c$ RSFQ circuits have recently been made by several groups, although the available Josephson junction fabrication technologies are not yet mature. The Chalmers group have demonstrated4 a circuit consisting of a truncated RS SFQ flip-flop (without the buffer junction in the reset channel) complemented by the necessary input and output circuits, using grain boundary junctions in a YBa$_2$Cu$_3$O$_{7-x}$ thin film. The use of a low-$T_c$ (lead-alloy) ground plane, however, has limited the circuit operation to helium temperatures. Recently, the Westinghouse group has demonstrated5 operation at 65 K of another circuit, designed as a two-stage SFQ shift register. This YBa$_2$Cu$_3$O$_{7-x}$ thin-film circuit did not have a ground plane, so that the inductances of the register loops were very large, and operation of only one cell (essentially, a multistable dc SQUID) has been demonstrated.4 In this letter we describe operation of a more complex all-high-$T_c$ circuit, almost similar in schematics to that studied in Ref. 2.

Our circuit [Fig. 1(a)] is nominally symmetric and includes two dc/SFQ converters (using Josephson junctions J1L, J2L, and J1R, J2R), two Josephson transmission lines (J2L–J4L and J2R–J4R), RS SFQ flip-flop5 (J5L, J6L and J5R, J6R) and readout SQUID (SFQ/dc converter, junctions J7L and J7R). If the inductive parameter $\beta_L = 2 \pi I_c L / \Phi_0$ of

\[
\sum_{k=1}^{5} I_{KL}^{-1} b_{k-1} / 2
\]

\[
\sum_{k=1}^{5} I_{KR}^{-1} b_{k-1} / 2
\]

FIG. 1. Single-layer YBCO thin-film circuit consisting of two dc/SFQ converters, two Josephson transmission lines (JTL), RSFQ flip-flop, and an SFQ/dc converter: (a) equivalent circuit; (b) micrograph of the fabricated sample. Hand-drawn thin lines mark locations of the Josephson junctions. Junction J0 was formed by mistake, and does not affect substantially the circuit operation.

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the flip-flop (where \( I_c \) is the effective critical current of junctions J6, while \( L \) is the total inductance of the loop) is larger than 1, the loop can have several stable flux states—see, for example, Ref. 5. Switching between the neighboring states that differ by a single quantum of magnetic flux trapped in the loop (i.e., setting and resetting the flip-flop) may be achieved by sending an SFQ pulse along the appropriate Josephson transmission line (JTL) biased by dc currents \( I_2-I_4 \). The pulse may be generated by junction J2 (L or R) by raising the corresponding external current \( I_1 \) above some threshold level \( I_t \). As a result the number of flux quanta in the dc/SFQ converter loop (inductance \( L_L \) or \( L_R \)) decreases by one. In order to restore the initial state of the converter, current \( I_1 \) should be decreased below another threshold \( I_t' < I_t \), so that a new flux quantum could enter the loop through the junction J1. Finally, junctions J5 (L and R) guard the flip-flop against stray SFQ input pulses: say, sending one more flux quantum along the left JTL after the flip-flop has already been set should lead to its fallout from the circuit via junction J5L. Switching of the flip-flop can be monitored by measuring the dc voltage \( V_{out} \) across the read-out SQUID [terminal A in Fig. 1(a)], provided that the dc bias current \( I_b \) is above the critical current \( I_b \approx I_{L+I_{R}} \) of the SQUID. The SQUID may be tuned to a bias point with high transfer factor \( \eta = |dV/d\Phi| \) by a proper choice of both \( I_b \) and the differential current \( I_{H} = I_{SL-I_{SR}} \), which changes the magnetic bias \( \Phi_x \) applied to the SQUID loop.

The circuit has been fabricated using a \( c_{L} \) YBa$_2$Cu$_3$O$_{7-x}$ film of thickness \( d = 50 \) nm which was grown on a LaAlO$_3$ substrate by the BaF$_2$ process. The film was then patterned [Fig. 1(b)] by optical lithography using PMMA resist and etched in 0.01% water solution of HNO$_3$. Josephson junctions were formed by direct e-beam writing using a scanning electron microscope (Philips CM-12). The electron irradiation dose per unit length \( \approx 0.5 \) C/m was chosen to provide the effective critical temperature of the junctions close to 30 K. The 5×5 mm$^2$ sample was mounted onto a holder providing reliable pressure contacts between the gold-plated beryllium-bronze springs and 100 nm thick gold contact pads deposited on the YBa$_2$Cu$_3$O$_{7-x}$ film. During the measurements, the holder was placed above the liquid helium surface in a storage dewar, and the temperature was controlled with stability better than 0.03 K. Low-frequency testing was carried out using a multichannel data acquisition system controlled by OCTOPUS software. For quantitative testing of the circuit, the dc currents biasing the JTLs (\( I_2-I_4 \)) and the flip-flop (\( I_4 \)) were fixed slightly below their critical values, and the output voltage \( V_{out} \) was recorded as a function of currents \( I_{1L} \) and \( I_{1R} \). In order to cancel linear crosstalk effects, the magnetic bias \( I_H \) of the SQUID was changed simultaneously according to \( \Delta I_H = \alpha I_{1L} + \beta I_{1R} \), where \( \alpha, \beta \) are small (~0.03) empirically found factors. Figure 2 shows a typical result of such an experiment at \( T = 26.0 \) K. Increase of \( I_{1L} \) beyond the threshold \( I_{1L} = 0.4 \) mA leads to a jump of \( V_{out} \), manifesting the change in the flux state of the flip-flop. If now \( I_{1L} \) is decreased to zero and increased again, no substantial change of \( V_{out} \) will result. However, if a similar pulse of \( I_{1R} \) with an amplitude above \( I_{1R} \approx 0.55 \) mA is applied before the next cycle of \( I_{1L} \), the output voltage returns back to the initial value as it should. The results of this experiment are presented in the time domain in the right part of Fig. 3 (single pulse pattern). The left part of this figure (double pulse pattern) shows that application of the second current pulse to the same input of the flip-flop does not change its state, in agreement with the concept of the circuit operation.

These results, however, cannot serve as the final proof of the correct operation of the system. One could argue, for example, that the flip-flop was switched directly by external currents \( I_1 \) sneaking along the superconducting electrodes of the JTLs to junctions J6. In order to exclude alternative interpretations such as this, we have carried out numerous additional measurements together with numerical modeling of the system using PSCAN software.

The critical current \( I_c \) of the geometrically identical junctions immediately after writing is a function of the effective critical temperature, which is defined by the e-beam irradiation dose. Apart from fairly insignificant beam instability during writing, the only additional source of junction-
to-junction critical current spread is the lithography, which may give \(\sim 10\%-15\%\) parameter spread. Therefore, the main cause of the critical currents spread is progressive annealing of the sequentially fabricated e-beam junctions at room temperature\(^8\) (the process of writing 15 junctions took about 8 h). From the known time lag between e-beam writing of each junction and cooling the sample below \(T_d\), where \(T_d \approx 250\) K is the temperature at which the annealing practically stops, we found their effective critical temperatures and hence critical currents at operation temperature. These calculated values of \(I_c\) (at \(T=26\) K they ranged from 0.08 to 0.35 mA) have been found to be in fair (\(\sim 15\%)\) agreement with the experimental critical currents of all parallel groups of junctions (like J1L, J2L, J3L, and J0) that could be measured. The only noticeable exception were the readout SQUID junctions J7L and J7R, nominally 2 \(\mu\)m wide (width of all other junctions was 4 \(\mu\)m). Real critical currents of these two junctions (\(\sim 0.035\) mA) were about twice as small as the calculated values, apparently indicating a substantial (\(\sim 1\) \(\mu\)m) undercut of the thin film edges.

Inductances of the superconducting loops were estimated from the independently measured effective penetration depth \(\lambda_\parallel = \lambda^2/d\) (at \(T=26\) K, \(\lambda_\parallel = 2.5 \pm 0.5\) \(\mu\)m) and the circuit geometry. For the mutual inductance \(M\) between the readout SQUID and the basic circuit this estimate gives \(\sim 20\) pH, in good agreement with the experimental result (19 \(\mu\)H). For the quantizing loop of the flip-flop the estimate gives inductance \(L = 25\) \(\mu\)H, for the input inductances \(L_J \approx 5\) \(\mu\)H, while the inductance of each JTL mesh is about 12 \(\mu\)H.

Numerical modeling using these values has shown that the circuit should really work as initially intended. Moreover, the calculated switching thresholds \(I_{IL} \approx 0.5\) mA, \(I_{IR} \approx 0.7\) mA are in reasonable agreement with the data (see above), considering the approximate character of the inductance estimates. The same can be said of the reciprocal derivatives \(D_i\) of the thresholds \(I_c\) over the JTL bias currents \(I_I\); for example, for the left half of the circuit the simulations give \(D_2 = -0.34\), \(D_3 = -0.53\), and \(D_4 = -0.76\), while in the experiment \(D_2 = -0.24\), \(D_3 = -0.32\), and \(D_4 = -0.62\). Most importantly \(|D|\) increases with \(i\); this shows that the farther the current injection point from junction J2 (and hence the closer it is to, say, J6) the weaker the influence of a particular dc bias current on the switching threshold. This result clearly indicates that it is junction J2 (rather than J6) that constitutes the bottleneck of the switching process, and hence the flip-flop is indeed switched by the dynamic SFQ pulses.\(^11\)

Finally, we have measured statistics of switching thresholds \(I_c\), by ramping up the corresponding currents \(I_I\) at a rate \(\sim 0.1\) mA/s. At 26 K, the statistics could be crudely fitted by the Gaussian distribution with the standard deviations \(\sigma_{I_i} \approx 9\) \(\mu\)A and \(\sigma_{I_R} \approx 12\) \(\mu\)A for \(I_{IL}\) and \(I_{IR}\), respectively. These numbers are to be compared with the estimates \(\sigma_{I_c} \approx 10\pm3\) \(\mu\)A and \(\sigma_{I_R} \approx 12 \pm 4\) \(\mu\)A, following from the thermal activation theory for the overdamped RSJ-model junctions [see, for example, Eq. (1) in Ref. 12], with the critical currents of junctions J2L and J2R calculated as discussed above, and the experimental values of the coefficients \(D_2\).\(^13\) This result shows that the switching statistics is dominated by the equilibrium thermal fluctuations.

To summarize, we have successfully demonstrated operation of a simple all-high-\(T_c\) superconducting RSFQ circuit at \(T = 26\) K. At these temperatures, thermally induced r.m.s. fluctuations of the switching thresholds are still considerably smaller than the persistent current \(I_p = \phi_0/L \approx 70\) \(\mu\)A induced by the switching between the neighboring flux states of the flip-flop. For our circuit, increase of temperature to 77 K (while keeping the critical currents at the same level by increasing the critical temperature of the Josephson junctions to about 80 K) would lead to \(I_\lambda \sim 4\) \(\mu\mbox{m}\) and \(I_p \sim 60\) \(\mu\mbox{A}\), while fluctuations of the switching thresholds \(\sigma \approx T^{2/3}\) would reach \(\sim 6\) \(\mu\mbox{A}\) (when reduced to one junction). Hence, the circuit could still operate at 77 K, although with a considerable rate of spontaneous switching between its stable states.\(^5\)

\[\Gamma \sim \omega_c \exp \left[-(I_p/\sigma)^{3/2}\right] \approx 10^{-1}\ \mbox{s}^{-1}\] A further improvement of the reliability, as well as fabrication of more complex high-\(T_c\) RSFQ circuits, will require a substantial increase of \(I_p\), via reduction of inductances by using thicker superconducting films and multilayer circuits. At this stage, quantitative modeling and optimization of the circuits will be necessary.

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4. To our knowledge, preliminary claims from other groups to successful testing of high-\(T_c\) RSFQ circuits have not been confirmed.
11. If junctions J1 presented the bottleneck, the derivatives \(D_i\) would have had the opposite sign.
13. This estimate assumes that all of the current \(I_c\) flows through the junction J2; we believe that this is true within \(\sim 30\%\).