High-temperature superconductor opening switch

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A jitter-free, repetitive opening switch made of $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ high-temperature superconductor is demonstrated. The switch conducts electrical current at no loss when it is superconducting. A pulse or pulse train of magnetic field on the order of 100 G causes the transition of the switch from the superconducting state to the resistive normal state and forces current to flow through a load resistor that is connected in parallel with the switch. Repetitive operation of this switch at rep rates higher than 1 kHz has been demonstrated.

The discovery of superconductors with superconductivity transition temperatures above liquid-nitrogen temperature[1] has stimulated a great deal of interest in the development of applications based on these new classes of materials. In the power applications of the high-temperature superconductors (HTSC), the zero resistance of the HTSC is used for power transmission or energy storage. For these applications, high performance electrical contacts and switches are desirable. Various high performance electrical contact techniques for HTSC applications have been reported.[2-4] In this work a jitter-free, repetitive switching of electrical current from a HTSC switch to a load resistor by means of magnetic controlling is studied. A HTSC switch made of $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ is schematically shown in Fig. 1. Rectangular bars of $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ are prepared by (a) mixing BaCO_3, Y_2O_3, and CuO, (b) repeatedly (three times) grinding and sintering at 935 °C for 16 h in oxygen atmosphere, (c) pressing at a pressure of 10 000 kg/cm^2 into the rectangular shape of 5 mm width and 75 mm length with thickness between 0.5 and 2 mm, (d) sintering at 950 °C for 6 h in oxygen atmosphere, and (e) cooling slowly in the furnace to 400 °C and staying at this temperature for 4 h. HTSC prepared by this process has the superconductivity critical current density around 160 A/cm^2 at 77 K and zero magnetic field according to the 1 μV/cm standard. Silver contacts are made on these HTSC bars by means of silver evaporation,[2] molten silver processing,[3] or heat-treated silver painting technique.[4] Copper wires are soldered to the silver contacts and arranged to minimize the interference caused by the magnetic pulse, i.e., to minimize the circuit loop that is exposed to the magnetic field. The finished HTSC bar is protected by acrylic spray coating.

Shown in Fig. 2(a) is the circuit diagram for the HTSC opening switch with the switch immersed in liquid nitrogen. The current source supplies a current equal to or less than the critical current of the HTSC switch to the outer two contacts on the switch. A low-resistance load, on the order of a few Ω, is connected between the inner two contacts. Without an applied magnetic field, the switch is superconducting and all the current from the current source flows through the switch with load current I_L equal to zero. When a magnetic field of tens of Gauss is applied, in a direction perpendicular to the current flow, to the central section of the superconductor bar between those two inner contacts, the HTSC that is exposed to the applied magnetic field becomes resistive as shown in Fig. 2(b). The amount of current that can be switched to the load is determined by the current divider rule based on the resistance of the HTSC and the load as well as silver contacts.

When a magnetic field is applied, the critical current of the HTSC switch decreases significantly with increasing magnetic field up to about 100 G and then decreases slowly with magnetic field. The current-voltage (I_s-V_s) characteristics of a HTSC switch with critical current equal to 8.4 A are shown in Fig. 3 as a function of the applied magnetic field. The horizontal axis is the switch current I_s flowing through the central section of the HTSC bar between the inner two contacts, and the vertical axis is the voltage drop V_s across the same section of the HTSC bar. As the magnetic field increases, the I_s-V_s curve shifts to the left at a rate that decreases with magnetic field between 20 and 100 G. For magnetic field between 100 and 200 G, that is, the highest magnetic field tested in this work, the I-V curve stays about the same. The dependence of ceramic HTSC current density on magnetic field may be attributed to the "weak coupling" effect between superconducting grains[5,6] in the HTSC bar and therefore is dependent upon the sample preparation pro-

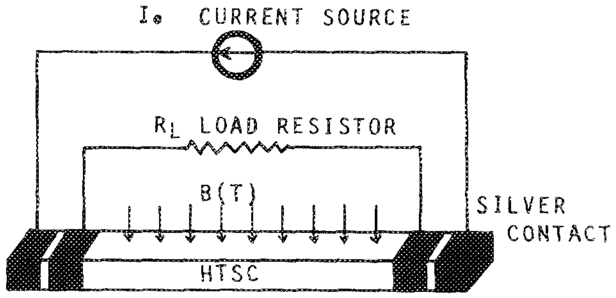

FIG. 1. Schematical representation of a high-temperature superconductor opening switch controlled by a magnetic field.

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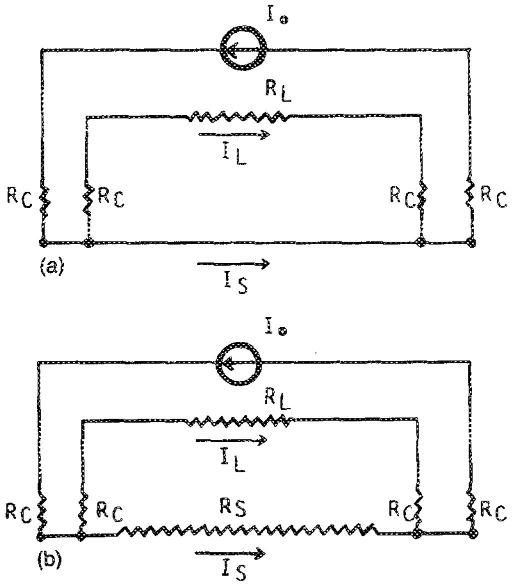

FIG. 2. Circuit diagrams for (a) the high-temperature superconductor switch without an applied magnetic field and (b) the HTSC switch with an applied magnetic field.

cess. The operation of the HTSC switch can be interpreted with the aid of a load line representing the I_s-V_s characteristics of the load resistor connected in an opening switch circuit as shown in Fig. 1 as well as the contact resistance between the load and the switch. For high performance silver contacts with the contact area larger than the cross-sectional area of the HTSC bar, the contact resistance R_c is less than 1 $\mu\Omega$ and can be neglected in this case. Therefore, the load line is a straight line represented by

$$I_0 = I_s + V_s/R_L, \qquad (1)$$

where I_0 is the current supplied by the current source and R_L is the load resistance.

Two load lines corresponding to 8 A power supply current I_0, and 3 and 0.1 mΩ load resistance R_L, respectively, are shown in Fig. 3 in conjunction with the I_s-V_s curves for the 8.4 A HTSC switch. The intersection between a load line and the I_s-V_s curve corresponding to the maximum applied magnetic field determines the distribution of the current from the current source between the load and the central section of the HTSC bar. As shown in Fig. 4, for the HTSC switch being tested a load resistance of 0.1 Ω will allow about 80% of the total current to be switched to the load while a 3 Ω load resistance will allow only 30% of the total current to be switched to the load. The switchable load current will increase, when all the other parameters are kept the same, if the HTSC bar is made longer or a HTSC with higher normal-state resistance is used since the I_s-V_s curves for the HTSC switch will shift upward with increasing normal-state resistance for the HTSC. When a magnetic pulse or pulse train is applied to the HTSC switch the waveform is determined by the magnetic pulse as well as the I_s-V_s characteristics shown in Fig. 3. A typical oscilloscope trace of the load current detected by a current probe is shown in Fig. 4. The rise time of the load current is determined by the time it takes for the magnetic field to increase to about 100 G. Therefore, a fast rising magnetic field will result in a rapid switching operation. The recovery of the HTSC switch after the magnetic field decreases to zero is fast enough for the operation of the switch at 1 kHz. Shorter fall time for the load current waveform is expected if a magnetic pulse with a fall time shorter than the one used in this experiment is applied.

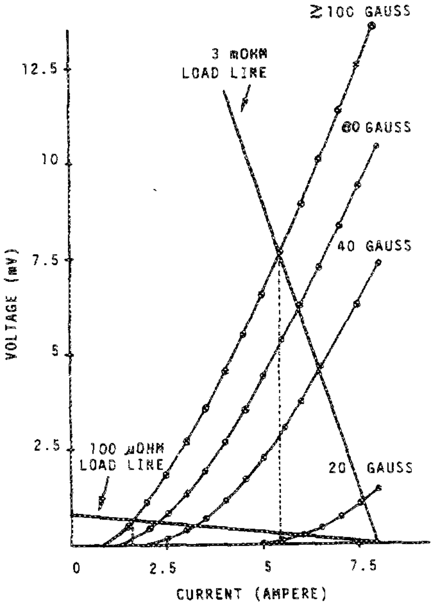

FIG. 3. I_s-V_s characteristics of an 8.4 A high-temperature superconductor opening switch with two load lines corresponding to load resistances of 0.1 and 3 mΩ, respectively.

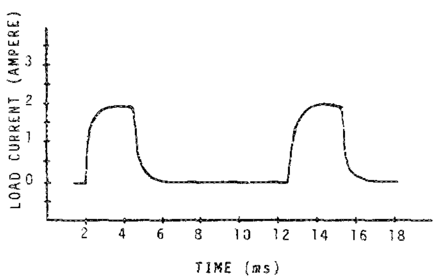

FIG. 4. Typical waveform of load current pulses when the high-temperature superconductor switch is exposed to magnetic field pulses of 120 G.

In summary, a jitter-free, repetitive HTSC opening switch has been demonstrated and studied. This switch is very useful as an opening switch for low-resistance loads. The "weak coupling" effect for superconducting grains in ceramic HTSC has been applied for the control of the opening switch with pulses of magnetic field around 100 G. Operation of this switch at a rep rate up to 1 kHz has been demonstrated. Further studies are being conducted for the exploration of the optimal performance of this class of HTSC opening switches. This work is supported by AFATL/SAH, Eglin AFB.

[1] M. K. Wu, J. R. Ashburn, C. J. Torng, P. H. Hor, R. L. Meng, L. Gao, Z. J. Huang, Y. O. Wang, and C. W. Chu, Phys. Rev. Lett. **58**, 908 (1987).

[2] Y. Tzeng, A. Holt, and R. Ely, Appl. Phys. Lett. **52**, 155 (1988).

[3] Y. Tzeng, J. Electrochem. Soc. **135**, 1309 (1988).

[4] Y. Tzeng and M. Belser, in *Superconductivity and Its Applications*, edited by H. S. Kwok and D. T. Shaw (Elsevier, New York, 1988), p. 174.

[5] G. Paterno, C. Alvani, S. Casadio, U. Gambardella, and L. Maritato, Appl. Phys. Lett. **53**, 609 (1988).

[6] D. Wong, A. K. Stamper, D. D. Stancil, and T. E. Schlesinger, Appl. Phys. Lett. **53**, 240 (1988).