NON-LINEAR RESISTIVITY MATERIALS FOR PULSE POWER APPLICATION

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SUMMARY:

Several types of conducting materials exhibit drastic resistivity changes due to heating, photon injection, or due to application of electric fields. Two types of materials that change resistivity due to heating to temperatures of the order of 100^0C have been investigated to establish whether they can be used to develop a reusable opening switch for high power inductive storage applications.

I. Introduction:

Various opening switch functions associated with high power inductive storage[1] are, at present, performed by such devices as explosively driven circuit breakers,[2] fuses[3] and combinations (staging) of these.[4] Explosively driven switches are used in applications including inductive storage systems powered by rotating machinery, where long conduction time and fast interruption are essential.[1] Fuses provide substantially faster opening time than explosive switches and are often used in inductive systems where capacitor banks provide the source of current. Fuse vaporization energy, derived from the current source, reduces the efficiency of the energy transfer from the inductor to the load. These types of switches cannot be reused. Other types of opening switches, which can be reused and can be applied for repetitive operation (and have very fast opening time), depend on the use of diffuse discharges. Such switches include plasma erosion switches[5] and electron-beam controlled ionized gas switches.[6] They are limited in their application by short conduction time and by complex, power consuming, control circuits (i.e., plasma and electron beam generators, respectively).

To combine the advantage of switches using solid conductors, such as fuses, and various types of circuit-breakers, with those of the gaseous opening switches that utilize relatively low energy density associated with the volume discharge, solid materials with non-linear resistivity have been examined for their applicability to high power inductive storage systems. Several of the change-of-state materials (with relatively low transition temperature) are highly promising candidates for developing reusable opening switches (for inductive storage) and closing switches with specialized characteristics such as extremely fast rise-time.

Table I lists characteristics of five major classes of materials that can, potentially, be developed into closing or opening switches[7]. Their "on" and "off" resistivities, ρ and ρ_0 are seen to differ by many orders of magnitude. Materials with magnetic field saturation (category 5) are used to change circuit inductance and are pulse shaping devices rather then switches.

Fig. 1 shows the non-linear resistivity of two materials, $BaTiO_3$ ceramic and carbon-filled polymer (CFP), with their properties and switching mechanisms described in references 8 and 9, respectively. These

TABLE I. NON-LINEAR RESISTIVITY MATERIALS FOR SOLID SWITCHES

Material	ρ_0 ("on" state)	ρ/ρ_0	Hold-Off Field (E)	Type of Trigger	Energy for Trigger*	Switching Time Limit	Comments
1. A. Semimetal -insulator transition (e.g. V_2O_3)	$10^{-4}\Omega$-cm	10^3-10^8	10^6V/cm	a) I^2R heating b) Pressure c) Laser	small	a) I^2R b) Acoustic Speed c) Laser Pulse	-opening/closing -bulk scalable -Mott transitions
B. Mott transition							
2. Change-of-state material							-opening -small samples tested
A. Poly-ethelene carbon filled	1 Ω-cm	10^4	20 kv/cm	I^2R	<10%	10μsec	-ok in parallel -series requires load sharing
B. Ferro-electrics (e.g. $BaTiO_3$)	1-100 Ω-cm	10^5	>10 kV/cm	I^2R	small	<1 ms	-opening -potentially large number of materials are available -has negative temp. coeff. before positive temp. coeff.
C. Solid-liquid	$10^{-5}\Omega$-cm	10^{10}	200 kv/cm	laser	100J/cm^3 of laser light	psec	-closing
3. Varistors	0.1Ω-cm	10^{10}-10^{12}	1-10 kv/cm	a) voltage b) light	a) small b) small	< 1 nsec < 1 nsec	-closing -bulk scalable
4. Magnetic		dL/dt	config, sensitive	saturation	small	10 nsec	-pulse shaping
5. Supercond.	0	x	(same)	thermal pulse	-	μsec	-opening

*Related to energy transferred by the switch.

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materials exhibit positive temperature coefficient (PTC) above temperatures of about 100°C, associated with the Curie temperature of the $BaTiO_3$ and with the phase transition of the carbon-filled polymer (CFP) from the crysalline form to amorphous state. The dramatic change of several orders of magnitude in the resistivity makes these materials suitable for true opening switches, i.e. for circuit elements that change from a conductor to non-conductor, without requiring recovery time for voltage hold-off. The resistivity of these materials is sufficiently low, so that even at relatively high current density a long conduction time (i.e., the "on" time) can be obtained. Because these materials are commercially available, they were chosen for initial investigation. The following sections describe the preliminary switching results and scaling relations, to be used in future experiments and evaluations.

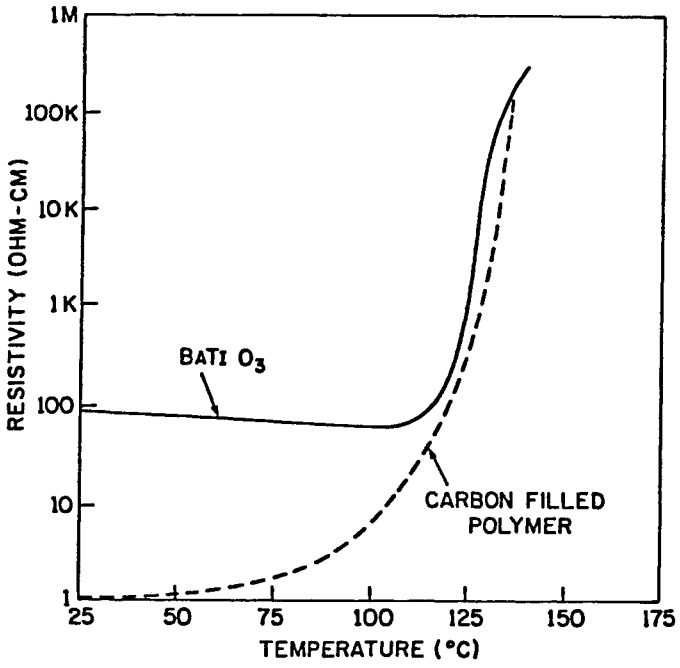

Fig. 1. Resistance characteristics for commercially available PTC thermal switching materials. Upper curve[8] for $BaTiO_3$ exhibits small negative temperature coefficient at lower temperatures. Lower curve for CFP[9] is characterized by weak resistance increase at these temperatures.

II. Electric Properties of $BaTiO_3$ and CFP and Their Scaling.

A. Semiconducting Polycrystalline PTC Materials

As Fig. 1 indicates, $BaTiO_3$ has a switching characteristic associated with very narrow temperature range, ΔT (of about 20°C). This makes it adaptable to triggerable circuits, i.e. to circuits with the switching element appropriately triggered to induce the conductivity change. The small temperature range allows the material to return to its initial conducting state with only small amount of heat removal. In contrast, because of its substantial increase of resistance at the temperature well below transition temperature, CFP --the other material chosen for the study-- must be cooled almost to room temperature to recover its initial resistivity. Thus, $BaTiO_3$ can, potentially, be used in burst output pulsers*, with minimum pulse-to-pulse separation dictated by the heat removal configuration. Because $BaTiO_3$ starts at substantially higher resistivity (~100Ω-cm) the applications may be limited by the physical size to currents of about 10 kA**, under conditions where long conduction time is required.

To relate the current density and switching time, a simplifying assumption of no loss of heat (generated by the ohmic heating) leads to a simple scaling relation between those quantities.[11] The conducting material increases in temperature, T, at a rate proportional to the electric power density input (given in terms of current density j):

$$\frac{dT}{dt} = \frac{\rho j^2}{C_v} \qquad (1)$$

where C_v is heat capacity per unit volume. Representing the resistance characteristic given in Fig. 1 by exponential form $\rho_0 e^{\alpha T}$, the solution of Eq. (1) becomes

$$e^{\alpha T} = 1 - \frac{\alpha \rho_0 j^2 t}{C_v} \quad . \qquad (2)$$

If the initial resistance increases by γ, such that $\rho = \gamma\rho_0$, then

$$\frac{1}{\gamma} = 1 - \frac{\alpha \rho_0 j^2 t}{C_v} \quad . \qquad (3)$$

$$t \simeq C_v/\rho_0 j^2 \alpha \quad , \quad \text{for } \gamma >> 1 \; . \qquad (4)$$

Equation (4) can be written in terms of the applied field $E = \gamma j \rho$:

$$t = C_v \rho_0 \gamma^2/\alpha E^2 \qquad (5)$$

Recognizing that the maximum value of j that can be passed by the non-linear material is determined by the maximum electric field E_m (i.e., $j = E_m/\gamma\rho$) the scaling for minimum opening time, t_{min}, is obtained:

$$t_{min} = C_v \rho_0 \gamma^2/\alpha E_m^2 \; . \qquad (6)$$

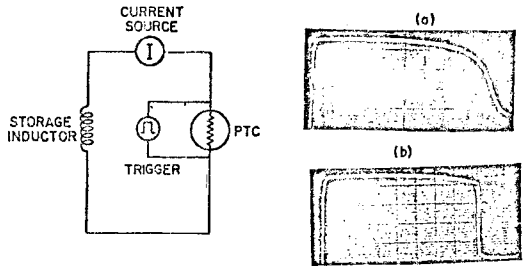

Fig. 2. Effect of trigger amplitude on the switching characteristic of $BaTiO_3$. Oscilloscope sweep rate is 1 sec/div.

*Pulsers providing a train of several closely spaced high power (10^{10} W) output pulses have been constructed, by using one opening switch per pulse within the train.[10]

**Ref. 7 indicates that practical $BaTiO_3$ ceramic systems, with resistivity less than 1Ω-cm, might become available.

The last relationship indicates the importance of the hold-off (breakdown) field of the non-linear materials in their ability to switch rapidly. Experimental confirmation of scaling relation (5) is given below.

However, because of very narrow temperature range, ΔT, over which switching occurs, low energy trigger pulses can be used to control large energy systems. Fig. 2 shows a circuit using a trigger, resulting in such performnce.

Fig. 2a shows switching of current that reflects the model associated with the Eq. (4) and (5), i.e., the transition to high resistance results from Ohmic heating by the source current. Not only is it possible to control the time of switching but also the rate of switching transition using an external high current, short duration, trigger pulse. At critical value of $E_{trigger}$ (Fig. 2b), the switching controlled by trigger power is achieved.

The value of the maximum field that could be supported across 0.127 cm thick sample was measured by applying an increasingly large driving potential to the sample. Thus, at 400V, a breakdown occurred at the surface of the sample, suggesting that $E_m = 3.1$ kV/cm. Using lower power supply potential of 20 V (i.e. applied field of 157 V/cm), measured switching time was compared with that predicted by the scaling equation (5). Taking $C_v \simeq 1.5$ J/cm^3, and noting from Fig. 2a that the 100 Ω-cm samples produced $\gamma \simeq 10$ with $E_m = 157$ V/cm, the switching time from Eq. (5) is ~ 2.5 sec for $\alpha = 0.23$, where α has been determined from resistivity vs. temperature curves given in Reference 9. The measured switching time is close to 1.5 sec, observed in Fig. 2a.

B. Polycrystalline Carbon-Filled Conductor (CFP)

Fig. 1 shows the resistivity of cold CFP to be about two orders of magnitude lower than that of the ceramic $BaTiO_3$. The high conductivity allows the CFP material to be used in a manner similar to the exploding fuses used in inductive storage circuits. This can be seen from the scaling derived below. Denoting quantities refering to fuses by a symbol F and those to CFP by a symbol C, relations for the energy deposited into the switch at the time that switching occurs, can be defined:

$$W_F = \int_{T_o}^{T_F} M_F \, C_{VF} \, dT + w_F \qquad (7a)$$

$$W_C = \int_{T_o}^{T_C} M_C \, C_{VC} \, dT + w_c \qquad (7b)$$

where T_o is room temperature, T_F is vaporization temperature of copper, and T_C is the transition temperature ($\sim 120°$ C) of the polymer from polycrystalline to amorphous state with attendant strong resistivity change of the carbon chains. The term w in the definitions (7a) and (7b) represents the energies associated with latent heat of transitions. For purposes of comparison of the cost in switching energy of the two materials, assume that they are to present the same resistance during conduction (i.e., cold resistance), so that $R_F = R_C$. Also assume that final inductive voltage to appear across the switching elements is V. Thus, for respective switch lengths L_F and L_C, the voltage is limited by the breakdown field of the material, E, so that $V = L_F E_F = L_C E_C$. The ratio of the two switching energies is (from Eq. 1):

$$\frac{W_C}{W_F} = \frac{M_C \int_{T_o}^{T_C} C_{VC} \, dT}{M_F \int_{T_o}^{T_F} C_{VF} \, dT} = \frac{M_C}{M_F} \, Y \, , \qquad (8)$$

where $W-w \simeq W$ and Y is the ratio of the integrals. Denoting densities of the materials by δ_F and δ_C and cross-sectional area by A_F and A_C, Eq. (8) becomes

$$\frac{W_C}{W_F} = \frac{\delta_C A_C L_C}{\delta_F A_F L_F} Y = \left(\frac{\delta_C}{\delta_F}\right)\left(\frac{A_C}{A_F}\right)\left(\frac{E_F}{E_C}\right) Y \, . \qquad (9)$$

Introducing the respective resistivities ρ_F and ρ_C, the requirement of initial switch resistance, $\rho_F L_F / A_F = \rho_C L_C / A_C$ yields

$$\frac{W_C}{W_F} = \frac{\delta_C \rho_C L_C E_F}{\delta_F \rho_F L_F E_C} Y = \left(\frac{\delta_C}{\delta_F}\right)\left(\frac{\rho_C}{\rho_F}\right)\left(\frac{E_F}{E_C}\right)^2 Y \, . \qquad (10)$$

For copper fuses, $\delta_C/\delta_F \simeq 0.1$ and with $\rho_C = 1\Omega$ -cm, $\rho_C/\rho_F \simeq 3.10^5$. As is shown later in the discussion of the experiments, $E_F/E_C \simeq 0.1$, giving $W_C/W_F \simeq 300\, Y$. To obtain approximate value of Y, consider that the conduction in CFP is by graphite only, so that the integral of C_V changes linearly with temperature from room temperature to the transition temperature of $\sim 120^0$ C. The integral of C_V for Cu (for temperature ranging from room to vaporization values) is about 30 times larger. Thus, $W_C/W_F \simeq 10$ and would approach unity for $E_C \simeq 30$ kV/cm. Actually, for very long conduction time E_F is lower yet so ratio w_C/w_F is more in favor of solid CFP.

The small amount of energy that must be deposited in CFP material to produce a drastic increase in resistivity allows it to be used in a manner similar to a fuse. The low switching temperature leads to reproducible behaviour, suitable for repetitive use (unlike one-shot operation of the fuse), provided sufficient cooling time is available. Ref. 9 indicates the nature of the mechanism responsible for strong change in resistivity with temperature.

III. Experimental Results

A. $BaTiO_3$ Ceramic

Small samples, 1.4 cm in diameter and 0.12 cm thick, produced by Keystone Carbon Co (Piece Part No.: RL5405-3.0-120-20-PTO) were pulse-tested using the circuit shown in Fig. 2. The current sources were either a d.c. power supply or 21.6 mF capacitor charged to 200 V, storing 440 J. The nominal resistance of the samples was 2.5 Ω and deviated by ± 0.5 Ω. The samples were rated for steady-state hold-off of 20 V. Using d.c. power supply to provide up to 20 A current, switching occurred at about 8 sec, converting electrical energy into Ohmic heat, depositing about 2.0 kJ/cm^3 into the ceramic. Without triggering, the current trace in Fig. 2a shows the opening time to be $\sim$1.5 sec. Using a 1200 μF capacitor charged up to 400 V (providing a trigger pulse energy of up to 100 J representing about 5% of energy required for switching,), the switching time was reduced to a minimum value of about 1 msec, seen for example in Fig. 2b. In a different experiment, designed to determine the breakdown fields, a capacitor current source, switched up to 100 A current. The results indicated

that the $BaTiO_3$, with resistivity in 300 Ω-cm range can hold-off field values of 3 kV/cm.

To determine power and energy handling capabilities of $BaTiO_3$ ceramics under pulsed conditions, 20 mF, 200 V capacitor was used as a 40A current source, providing 80 msec conduction before the switch opening. As 3.6 mF, 140 V capacitor triggered the switch, the opening time was about 1 to 10 msec, as in the previous 8 sec conduction time experiment shown in Fig. 2. The relative energies expended in the switch were 320 J over first 80 msec and 35 J associated with the trigger. Using the definition of the switching power, given in the footnote above, the power density associated with $BaTiO_3$ is $>4 \times 10^4$ W/cm^3. The switching efficiency is ∿ 90%. As the power is increased beyond this level in the test samples, voltage breakdown occurs. It appears to be a surface cracking, independent of the medium (such as air or oil) which surrounds the sample.

B. Carbon-Filled Polycrystalline Material

Carbon-filled polycrystalline material has resistivity substantially lower[9] than that of commercially available $BaTiO_3$. CFP modules are available as a current limiter device with trade-name "Polyswitch". Its resistivity is in 1Ω-cm range. Units made by RAYCHEM having steady state current rating of 9 A, were tested with currents up to 10 kA conducting for 100 to 500 μs and provided circuit interruption similar to that achieved with fuses. The switch performance closely resembles that of fuses used in a similar circuit. RAYCHEM production part PSR 20528 was used in these tests. Table II summarizes the characteristics of the circuit and switch performance.

Table II: Opening Switch Characteristics

A. Circuit Parameters

Energy stored (at 400V)	1000 J
Peak Current	2 KA (Resistance limited)
Charging time	500 μsec
Load Resistance	0.125 Ω

B. Switch Characteristics

Area	8 cm^2
ρ_0	1 Ω-cm
Generated Field	2 kV/cm
Opening Time	40 μsec
Efficiency	∿ 90%
Use	Resettable

Although the CFP switch is capable of resistance changes of 10^5, actual resistance values are established by circuit parameters. For example, the 0.125 Ω load resistance limits peak voltage (and therefore thermal energy to the CFP) to 75 volts For these tests, CFP initial resistance, R_0, was 9 mΩ. Peak switched current was 1 kA at approximately 550 μs. After this test, initial switch resistance has degraded to 12 mΩ, . No further degradation occurs, with the switch operated repeatedly at approximately 2 minute intervals.

The performance of CFP can be characterized as a resettable fuse. Table II, comparing the characteristics of the Polyswitch with those of the copper fuse exploded in air, provides the key points for assessing the Polyswitch performance and scaling for higher power applications. Because of the factors controlling the scaling (e.g., given by Eq. (10)) the switch efficiency in inductive store applications can potentially be better than with existing fuses.

V. Conclusions

Recently, development of a variety of solid materials with non-linear resistivity points to potential application of these materials as opening switches. The results of the experiments performed on materials that depend on thermal control of resistivity, $BaTiO_3$ and CFP, provide scaling relations that indicate future uses of such materials in opening switch development. One important feature that was demonstrated namely, the reusability of the switch, indicates that they can be employed in generating high repetitive frequency pulse bursts such as those achieved with explosive switch and fuse combinations discussed in Ref. 10. In such an application, one opening switch per pulse (in a given pulse train) is required.

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