FAST OPTICALLY TRIGGERED SUPERCONDUCTING SWITCH FOR HIGH-POWER VOLTAGE TRANSIENT GENERATION

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Abstract

It was shown that the generation by a super-conducting, light triggered switch of electrical pulses having sub-nanosecond rise times and high (up to several hundred V) amplitudes is due to the simultaneous optical and electrical demolishing of the superconducting state. The biasing of the superconductor by a short (nanosecond) electric pulse up to the appearance of the "mixed" state significantly decreases the energy of the light pulse necessary for high-power voltage transient generation.

I. INTRODUCTION

The physical processes which are responsible for the generation of voltage transients using a super-conducting, optically triggered switch are not random in nature and, for this reason, there is no time "jitter" between the generated voltage transient and the optical pulse. UWB pulses generated in this way [1] can thus be successfully used in high-resolution impulse radar such as GPR or in detectors of living objects hidden behind solid obstacles. Both these applications require pulses having sub-nanosecond rise times and amplitudes of the order of several hundred volts. It was demonstrating in [2] that such pulses are generated by the illumination of a $Y_1Ba_2Cu_3O_{x-\delta}$ film when the current passing through the superconductor is biased by an electrical pulse of nanosecond duration and the super-conducting material is thereby transforms into a "mixed" state. In this article, a more detailed analysis of the processes responsible for light induced high-power switching is presented and discussed.

II. EXPERIMENTAL DATA

The experiment was performed using switches made from thin (0.1-0.6 μm) Y-Ba-Cu-O film tapes fabricated by magnetron sputtering, laser ablation or MOCVD technique. The critical temperature (T_c) and the current density (j_c) at 78K of these tapes varied from 80K to 93K and from 0.1 to 10 MA/cm^2, respectively. The switch was designed in a shape of 50 Ohm impedance micro-strip transmission line (see Fig. 1) consisting of a metallic background (1), dielectric plate (2), coaxial-type connectors (3), central conductor (4) and super-conducting tapes (5). The tapes were connected in series to each other and grounded to the metallic background (1) of the transmission line. They were positioned such that the area illuminated would be about 1 cm^2. Such design enables the use of the largest portion of the light "spot", thus minimizing the losses of light pulse energy due to the circular, disk-shaped illumination area generated by the light source. Moreover, the "meander"-shaped positioning of the super-conducting tapes decreases the value of the magnetic field at the edges of these tapes. In order to minimize the current concentration at the "twist" portion of the "meander", this region had metallic blocks made from a thick In layer.

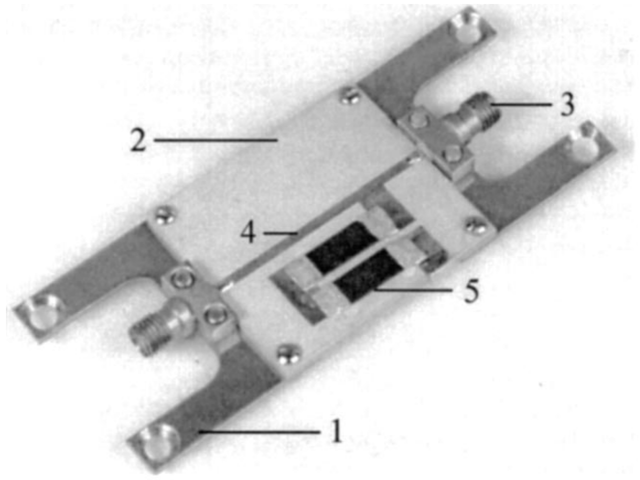

Figure 1. Outside view of switch

The detailed description of the experimental setup used for these investigations is presented in [2]. For the illumination of the superconductor, short (about 150 ps) single or low-repetition rate (12 Hz) 1.06 μm wavelength optical pulses having energy up to 1 mJ were generated by a YAG laser. A part (about 20%) of this energy was used for the triggering of the nanosecond electrical pulse generator based on a spark-gap switch. As a result, prior to their illumination, the super-conducting films were biased by

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14. ABSTRACT

It was shown that the generation by a superconducting, light triggered switch of electrical pulses having sub-nanosecond rise times and high (up to several hundred V) amplitudes is due to the simultaneous optical and electrical demolishing of the superconducting state. The biasing of the superconductor by a short (nanosecond) electric pulse up to the appearance of the mixed state significantly decreases the energy of the light pulse necessary for high-power voltage transient generation.

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short (15 ns) electrical current pulses and the light pulse action was delayed according to the beginning of the current pulse in time. The super-conducting switch was cooled by direct contact with liquid nitrogen. For this reason the film was illuminated through a 10 mm thick liquid nitrogen layer. The registration of the generated electrical pulses was performed by a high-speed, real time oscilloscope. The design of the switch and measurement circuit enabled the investigation of the dynamics of electrical pulses having 300 ps rise times and amplitudes up to 4 kV.

III. RESULTS

The dynamics of photo-response for films of various j_c and T_c as a function of film thickness (d), over-current through the superconductor (I) and light pulse fluence (F) were investigated.

It was obtained that the photo-response dynamics at constant F and $I \leq I_c$ (I_c is critical current) strongly dependant on the thickness of the film. If d is of the same value as the light penetration depth (L) (less than 0.15 μm), the duration of the voltage transient does not exceed the characteristic time of the measurement circuit (0.3 ns). At $d > L$, the voltage transient consists of two "steps". The duration of the first "step" is the same as that which is generated in the case when $d < L$. However, the second step is much longer and lasts several ns. The relative part of the whole amplitude generated during the first "step" decreases as the thickness of the film increases. For this reason, at $d \approx 0.6–0.7$ μm, the first "step" disappears and the whole transient is such as the second "step", i.e. a slow increase of the voltage during 10 ns.

The study of the photo-response dynamics in tapes with $d < L$ showed that a voltage transient can be generated even if $I > I_c$, i.e. when the superconductor is in a "mixed" state. Fig. 2 shows the dynamics of the electrical response to optical illumination at different currents flowing through the super-conducting tape. The dotted curves correspond to the "non-illuminated" state of the tape. The solid curve demonstrates the transients generated as a result of illumination. A typical light-induced voltage transient amplitude (V) vs. current (I) dependence has a maximum (Fig. 3). This occurs because at $I > I_c$, an initial resistance (R_i) due to magnetic flux flow appears in the tape [3]. As the amplitude of the voltage transient is proportional to the $R_n - R_i$ (R_n—resistance in illuminated state,) the maximum value of this amplitude is reached when the voltage (U) in the pulse-forming network is:

$$U = \frac{1}{16n}\left[(2R_n + Z)^2 - (Z - 2nI_c)^2\right] \qquad (1)$$

Here *Z* is 50 ohms and *n* characterizes the straightness of the voltage vs. current dependence in the resistive state.

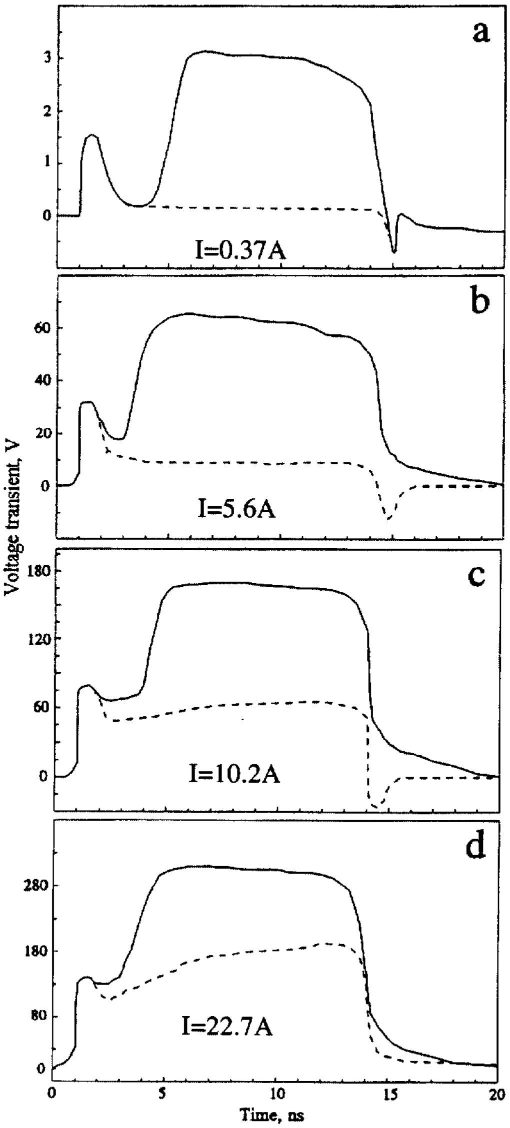

Figure 2. Voltage transient response to an optical pulse at various bias current.

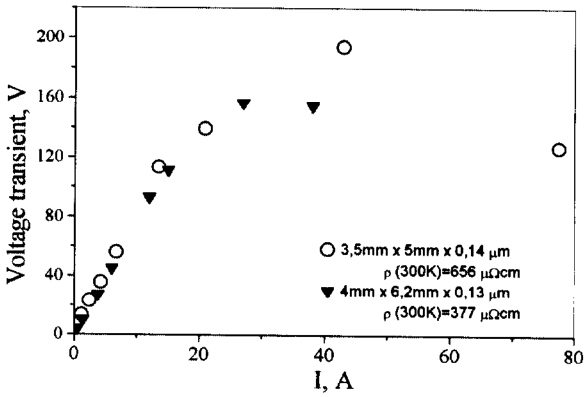

Figure 3. Generated voltage transient vs. bias current dependence for films prepared by magnetron sputtering (▼) and laser ablation (o).

The investigation of the dynamics of the generated voltage pulse showed that the light-induced resistive state is maintained the whole time during which the electrical current flows through the tape. However, as can be seen from the voltage waveforms presented in Fig. 2, there is a slow decrease in voltage at the top of the pulse. This decrease is due to the recovery process during which the tape transits from its high-resistive state to its low-resistive state. It should be noted that the "falling-shape" voltage pulse was obtained even when the pulse generated as a result of electrical switching (see dotted line of Fig. 2d) had an "increasing" shape of its top. Fig. 2 also demonstrates that at constant light fluence in the case of a low value of the over-current ($I - I_c$), the tape returned back to its super-conducting state as the bias current pulse action finished. The "negative" current pike at the end of the generated pulse (see Fig. 2a) is evidence of this event. However, an increase in over-current makes the recovery process significantly slower and, for this reason, there are no "negative" current pikes in the waveform of the generated pulse (see Fig. 2b,c,d). The investigation of the voltage transient amplitude (V) vs. light pulse fluence (F) dependence (Fig. 4a) obtained when $I < I_c$, showed that up to critical fluence (F_{c1}) this amplitude is zero; however, at $F > F_{c1}$ it increases and tends to plateau when F nears F_{c2}. A further increase of the F induces the appearance at $F = F_{c3}$ of the second "step" in the V(F) dependence. An increase of current (I) through the superconductor up to the value when the material is transformed into its mixed state (Fig. 4b) causes a significant decrease of F_{c1} and F_{c2}, and a slow increase of the F_{c3}. As can be seen from Fig. 4b, the amplitude of the voltage transient increases several times.

IV. DISCUSSION

The obtained results demonstrate that a short electrical pulse is able to create in a super-conducting tape a high (up to hundreds A) current without causing any irreversible changes of this tape. This makes possible the generation of high-power electrical pulses by means of the light triggering of the tape. This high-current regime requires super-conducting films having critical current density of no less than $j_c = 10^6 - 10^7$ A/cm^2. The reasonable dimensions of a thin-film switch designed in the shape of a coplanar wave-guide require that the area for illumination be about 1 cm^2.

As it can be seen from Fig. 2, high amplitude electrical pulse generation is achieved when the current through the tape is close or even higher then the critical current I_c. In this case, the increase of the tape resistance because of the illumination is more complicated than that in the case of low-power [1] pulse generation. There are two possible situations at which a fast electrical response to optical illumination appears. In the first situation, the light influences the whole volume of the film ($L > d$), in the second one ($L < d$), the light acts only to the light penetrating depth while the rest of the film is switched to the resistive state by the electrical current. Depending on the fluence (F) of the light and the value of the over-current ($I - I_c$), the following processes can be produced at $L > d$: i) switching from a super-conducting state to a "mixed" state (S-M transition), ii) switching from a low-resistance "mixed" state to a high-resistance "mixed" state (M_1-M_2 transition), iii) switching from a super-conducting state to a normal state (S-N transition) and iv) switching from a "mixed" state to a normal state (M-N transition). At $L<d$, a fast optical response is detected when, as a result of illumination, a part of the film is transformed into the N state while the other part acquires the M state. In this case, the tape can be imagined as a system made of two resistive layers (N and M) which are connected in parallel to each other.

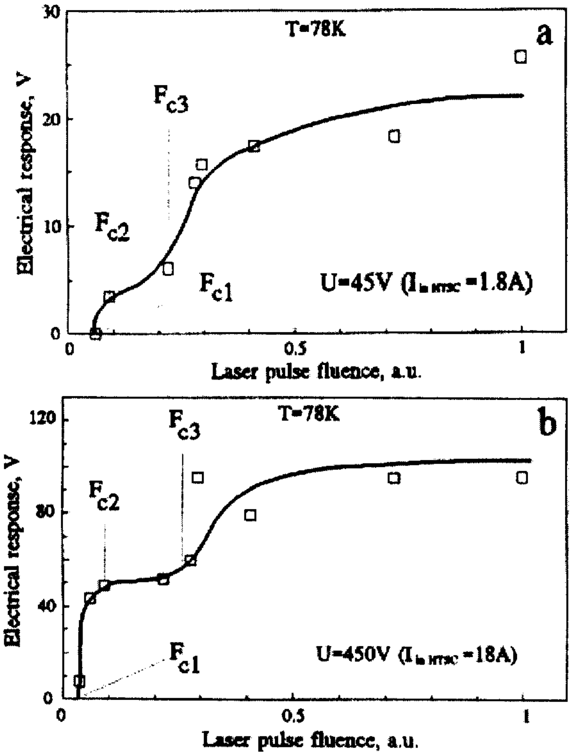

Figure 4. V(F) dependence for the YBaCuO/MgO: (4.5 mm × 6 mm × 0.25 μm, T_c^{on} = 87.4 K and I_c(78 K) = 13.9 A.)

The behavior of the generated voltage transient rise time indicates that the heating of the superconductor by the light pulse is very important for high-power pulse generation. The "two step" shape and the "slow" switching waveforms obtained in the case when $d > L$ can be explained by the transferance of heat from the "illuminated" region to the substrate. This shows that, most probably, the light action on the superconductor is bolometric in nature. For this reason, the slow heat flow through the substrate is responsible for the "long" recovery process from the N-state to the S-state and this helps to maintain the high-resistance state for several ns. In a high-current regime, the additional heat dissipates because of electrical current induced Joule's heating. As a result, the N-S recovery time increases.

For practical applications, it is very important to understand the processes responsible for V vs. F dependence behavior. Our proposed explanation of the results presented in Fig. 4 a,b is based on fact that the change of the light fluence F changes the depth in which light transforms superconductor to the N state and temperature of the material in this depth. In the case when $I < I_c$ and at a small F value, the light pulse is capable of changing only a part of the film depth from the S to the N state. In such case, the current density (j) in the rest (the super-conducting part) of the film is less than j_c and there is no electrical response to the illumination. However, an increase in F decreases the difference between j and j_c. For this reason, at F_{c1}, $j = j_c$, the whole sample is transformed to the resistive state. The F_{c1} depends on film thickness (d), light penetrating depth (L), U and j_c in the following way:

$$F_{C1} = F_o \, exp\left[\frac{d}{L} - \frac{2U}{j_c LZ}\right] \tag{2}$$

Here $F_0 = L \cdot D \cdot C \cdot (T_c - T_o)$ is the energy necessary to increase the temperature of the layer, the depth of which is equal to L, from ambient temperature T_o up to T_c, D is material density, and C is specific heat.

A further increase of the F causes an increase in V since the resistances of both parts of the film, that transformed to the N state by the light and that by the electrical current, change their resistance from a lower to a higher value. The V(F) curve in this case can be described by the same law up to a flush at which all the Cooper pairs in the non-illuminated (remaining) layer are broken by the current. Such state is achieved at:

$$F_{C2} = F_o \frac{\rho_c}{\rho_c - \rho_o} \left\{ exp[\frac{d}{L} + \frac{2\rho_o}{LZ} - \frac{2U}{LZ}(j_c + \frac{\rho_o}{n})] - \frac{\rho_o}{\rho_c} \right\} \tag{3}$$

Here ρ_0 and ρ_c is the film resistivity at ambient (T_o) and critical (T_c) temperature, respectively, and n is the coefficient in the $\rho = n(j - j_c)$ dependence.

At $F > F_{c2}$, the thickness of the layer with the resistivity ρ_0 decreases when F increases. As a result, the generated voltage transient amplitude V depends on F as follows:

$$V = \frac{U}{1 + \frac{Zd}{2\rho_o} - \frac{LZ}{2\rho_o} \cdot ln \frac{\rho_o}{\rho_c}\left(1 + \frac{\rho_c - \rho_o}{\rho_o} \cdot \frac{F}{F_o} \right)} \tag{4}$$

When F reaches the value

$$F_{C3} = F_o \, exp\left(\frac{d}{L}\right) \tag{5}$$

the light induces the N state in the whole volume of the film. A further increase of V with the increase of F is due to the heating of the film. For this reason,

$$V = \frac{U}{1 + \frac{LZ}{2\rho_o} ln\left[exp\left(\frac{d}{L}\right) + \frac{\rho_c - \rho_o}{\rho_o} \cdot \frac{F}{F_o} \right] - \frac{LZ}{2\rho_o} ln\left[1 + \frac{\rho_c - \rho_o}{\rho_o} \frac{F}{F_o} \right]} \tag{6}$$

V. CONCLUSIONS

It was concluded that high-amplitude (up to 1 kV) sub-nanosecond duration voltage transients can be generated using a super-conducting optically triggered switch. The change of the resistance of the superconductor is due to simultaneous action of light and electrical current on Cooper pairs breaking process. The biasing of the superconductor by short high-current electrical pulse significantly reduces the fluence of laser pulse necessary for superconducting switch triggering.

VI. REFERENCES

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