Switching characteristics for thin films of high-T$_c$ superconductors driven by optical and current pulses with varied lengths

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Abstract. This work proposes a method for lowering the energy of an optical impulse required to switch superconducting key elements, based on driving such a components with the use of current and optical radiation impulses with varied lengths. The investigation was conducted with the aid of numerical modelling of the superconducting switching element response for a structure composed of a thin YBa$_2$Cu$_3$O$_{7-x}$ superconducting film deposited on a sapphire substrate (Al$_2$O$_3$) with a buffer layer composed of strontium titanate (SrTiO$_3$). It was proven that thanks to the driving with control impulses of varied lengths, it is possible to switch such elements with 1.6 - 3.5 times lower energy of the optical impulse and the current slightly higher than the critical current, as compared with the switching mechanism employing impulses with the same length.

1. Introduction
Evolution of the digital technology requires development of increasingly fast signal switching elements. One of the most promising and perspective means of achieving this particular goal is the utilization of superconducting materials. Digital input/output circuits based on high-T$_c$ superconductors (HTS) can achieve switching frequencies at the order of 1 THz [1]. One of the vital features of superconducting switches – apart from the high switching speed – is the low amount of energy emitted by such electronic components. It is estimated that it can be lowered as far as $10^{19}$ J/bit [1]. This particular energy has a direct impact on the operation reliability of such a circuit. One of the possible operation principles for superconducting switching elements can be based on transition of the given material from the superconducting (S) state into the normal metal state (N), caused by electric current, magnetic field, optical radiation or microwave impulses [2,3]. The switching energies of the electronic elements under development are higher when compared with the aforementioned value, since such components feature a number of energy loss mechanisms, which are not accounted for in the balance estimations. One of the ways to boost efficiency of the HTS-film switching process is through the application of simultaneous current and optical impulses [4].

This work proposes therefore a method for lowering the energy of an optical impulse required to switch a HTS element, based on driving such a components with the use of current and optical radiation impulses with varied lengths.
2. The Method
The superconducting switching elements are typically manufactured in the form of thin-film structures with a superconducting layer forming a micro-bridge. The experimental research commonly utilizes high-Tc superconducting materials (HTS), with YBa\textsubscript{2}Cu\textsubscript{3}O\textsubscript{7-δ} as an example of a typical material. In order to obtain the highest possible quality HTS-layers, the substrate and the superconducting material are typically separated with a buffer (intermediate) layer with a crystallographic structure compliant with the HTS-material in question.

In this work, it is hereby proposed to utilize the mathematical-physical modelling method for conductivity switching processes in thin HTS-films to obtain the characteristics for HTS-keys driven with current and optical impulses. The geometric model [5,6] comprises five parallel and unlimited layers: a superconducting material, a buffer layer, a substrate and a couple layers modelling the contact regions. The superconducting layer is subject to an optical radiation impulse with the energy density $E_F$, and it is additionally polarized with the electrical current $I$. The external surface of the substrate is cooled with liquid nitrogen to the final temperature of $T_c,b$. The analysis of the process of destruction and recreation of superconductivity phenomenon in such structures conducted in [5] indicated that with the film thickness $h > 10 \text{nm}$ and the time scale $\tau > 1 \text{ns}$ the switching between the superconducting (S) and normal (N) states is mainly controlled by the bolometric mechanism. Heating of the superconducting layer occurs due to emission of the Joule’s heat and absorption of the incident optical radiation. The energy generated in the layer is then transferred to the thermostat via thermal conductivity mechanism. Heat abstraction results in recreation of the superconductivity. In the results of all the aforementioned processes, a resistive response of the key $R(\tau)$ is thus observed.

The modelling of the HTS-key response was conducted for a structure composed of a thin YBa\textsubscript{2}Cu\textsubscript{3}O\textsubscript{7-δ} superconductor film deposited on a sapphire substrate (Al\textsubscript{2}O\textsubscript{3}) with a buffer layer composed of strontium titanate (SrTiO\textsubscript{3}). The thicknesses of the individual layers were defined as follows: superconductor $h_s=0.2 \mu\text{m}$, buffer $h_b=1 \mu\text{m}$ and substrate $h_s=0.5 \text{mm}$. The micro-bridge dimensions were assumed to be equal to $20 \mu\text{m} \times 2 \text{mm}$. The resistivity of the HTS-film in the phase transition region N-S is approximated using a two-dimensional, non-linear function $\rho(T,j)$ of temperature and current density [6] using initial $T_{c,b}$ and final $T_{c,e}$ temperatures of the superconductor phase transition, critical current density $j_c$, and the specific resistivity $\rho$ in the N state. The calculations were conducted for a YBa\textsubscript{2}Cu\textsubscript{3}O\textsubscript{7-δ} -film of a very high quality: $T_{c,b}=90 \text{K}$, the superconductor transition width with the lack of conductivity current was estimated as $\Delta T_{c}=1 \text{K}$, $j_c(78 \text{K})=10^8 \text{A/cm}^2$, $\rho(T_{c,b})=0.1 \text{mΩ cm}$. The thermal conductivity for YBa\textsubscript{2}Cu\textsubscript{3}O\textsubscript{7-δ}, SrTiO\textsubscript{3} and Al\textsubscript{2}O\textsubscript{3} were assumed to be equal to: 2; 5 and 900 W/m K, respectively, while the thermal boundary resistance: HTS-film – buffer layer and buffer layer – substrate was estimated at $R_{T,I}=5 \times 10^8 \text{m}^2 \text{K/W}$ [7]. The remaining parameters used for calculations can be found in [4].

3. Control characteristics for HTS-keys
The HTS-switches operate in the optimum mode only when the superconductor reaches the N state corresponding to the initial phase of the N-S-transition and does not suffer from overheating. Therefore in this paper it is proposed to control the HTS switching element with the aid of an optical and current impulse with varied lengths: $\tau_F$ and $\tau_I$. The energy of the optical impulse $E_F$ is selected in such a way that the film temperature at time $\tau_F$ reaches $T_{c,b}$ i.e. the key switches on completely. The current impulse (longer than the optical one) is used to sustain the key response signal at the level close to $R(T_{c,b})$. The current amplitude $I$ is selected in such a way that the HTS-film temperature at time $\tau_I$ also reaches $T_{c,b}$, which corresponds to the compensation condition for the thermal power guided to the thermostat via the Joule’s heat generated in the superconducting film.

The modelling of the operation of HTS switching elements was conducted for rectangular current and optical radiation impulses which were started at the same time. The impulse length $\tau_I$ was varied between $1 \mu\text{s}$ and $5 \mu\text{s}$, while $\tau_F=(0.1-1)\tau_I$, which was defined in such a way to compare the obtained results with [8], where the control characteristics for the analogous HTS-structures driven with current and optical radiation impulses of the same length $\tau_{imp}$ were presented. The said paper indicated that the

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most significant reduction in the response switching time $\tau_{sw}$ due to introduction of the buffer SrTiO$_3$ layer in the HTS-structure based on Al$_2$O$_3$ substrate was observed for the $\tau_{imp}=5\mu$s and $h_b=1\mu$m.

Figure 1 depicts the obtained relations between the optical impulse energy $E_F$ (figure 1.a) and current amplitude $I$ (figure 1.b) and the duration of the optical impulse $\tau_F$ in the proposed control mode for various lengths of the current impulse $\tau_I$. Along with the decrease in the $\tau_F$ in relation to $\tau_I$, there is also a significant decrease in the value of $E_F$ energy. The amount of radiant energy required for turning the HTS-switch on under $\tau_F=\tau_I$ is between 3.5 (for $\tau_I=5\mu$s) and 1.6 (for $\tau_I=1\mu$s) times larger when compared with the system parameters for an optical impulse 10 times shorter than the current impulse. In such a system, the current keeping the key switched on varies by approximately 2% and is only slightly higher than the critical current at $T_o$ ($I_c(78K)=40mA$). The decrease in the $E_F$ energy results from a decrease in the amount of heat guided to the substrate of the HTS-structure and then to the thermostat when the key is switched on for shorter $\tau_F$. A vital role in the process of maintaining the heat in the superconducting layer is played by the buffer SrTiO$_3$ layer [9].

![Figure 1](image.png)

**Figure 1.** A relation between the optical impulse energy $E_F$ (a) and current amplitude $I$ (b) and the duration of the optical impulse $\tau_F$ in the proposed control mode for various lengths of the current impulse $\tau_I$. 
A decrease in the $E_F$ energy coupled with the decrease in $\tau_I$ with the constant optical impulse duration $\tau_F$ (figure 1.a) is caused by the reduced amount of heat accumulated in the HTS-structure during the process of switching the key on. This in turns results from the differences in the shape of the heating curves for the HTS-film (figure 2.a). The process of switching a key on (figure 2.a and 2.b) has two distinctive phases: the first one – until the inflexion of the heating curves at approximately $1\mu s$ – when the increase in the key resistivity occurs mainly due to the heating of the structure with the optical impulse, and the second one – where the HTS-film is switched into the N state. During the second phase the film is heated predominantly by the electrical current due to emission of the Joule’s heat. The increase in the temperature and resistance is highly non-linear in this phase which may result eventually in a thermal instability of the examined structure. This particular phenomenon is caused by the strong non-linear relation $\rho(T)$ in the region of the S-N-transition. The coexistence of the aforementioned two heating mechanisms within the HTS-film determines the course of the heating curve. To maintain the key in the on state in the case of longer current impulses, the required current

![Figure 2](image.png)

**Figure 2.** Temporal characteristics for temperature (a) and resistance (b) of the HTS-microbridge with a simultaneous interaction of an optical impulse with $\tau_F=2\mu s$ and a current impulse with varied duration time $\tau_I$.  

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amplitude \(I\) is lower (curve 5 in figure 1.b). Therefore, during the process of switching the given key on, the required \(E_F\) energy is higher. Thus, the heating curve for \(\tau_I=5\mu s\) (figure 2.a) is located above the respective curves for shorter \(\tau_I\), which in turns causes more significant heat accumulation in the examined structure.

After the current is switched off, the final N-S-transition temperature increases significantly (reaching the value of \(T_{c,j=0}=86.7\text{K}\)), which means that the key response is switched off very rapidly. The switch-off time \(\tau_{\text{off}}\) (figure 2.b) is estimated at 20ns – 30 ns for the \(\tau_I\) equal to 2\(\mu\)s - 5\(\mu\)s, respectively. This phenomenon is further favoured by relatively small thickness of the structure \(x_{\text{off}}\) (respectively, between 0.20\(\mu\)m and 0.25\(\mu\)m). Thickness \(x_{\text{off}}\) indicates that part of the structure which is heated, in the moment \(\tau_I\), above the switch-off temperature \(T_{\text{off}}\). The key is switched off when its resistance is lower then \(0.01 \cdot R(T_{c,b})\). It occurs at temperature lower then \(T_{\text{off}}\). Such values of \(x_{\text{off}}\) means that in order to effect the switching off process for the examined key, it is necessary to abstract the heat only from the superconducting film, or alternatively also from the ultra thin region of the buffer layer adjacent to the micro-bridge. Due to the very short \(\tau_{\text{off}}\) time, the response switching time \(\tau_{\text{sw}}\) is virtually equal to the switch-on time \(\tau_{\text{on}}\), which in turns is uniformly defined by the control mode and must be equal to the length of the radiation impulse \(\tau_{\text{r}}\).

The proposed control mechanism allows therefore not only to lower the energy of the individual optical impulses required to switch the HTS-key on but also maximally reduce the response switching time.

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