Proceedings of the 14th International Symposium Ultrafast Phenomena in Semiconductors, Vilnius 2010

Applicable Damage of High-T_c YbaCuO Superconducting Tapes by Current and Laser Pulses

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Damage and irreversible damage of YBaCuO tapes with high density current after switching from superconducting to normal state are investigated. Quasi-homogeneous current distribution across the tape in superconducting state can cause perfect tape damage or irreversible damage when current is slightly above critical value. The model of the tape heating during the optically initiated switching from superconducting to normal state is proposed. Analysis of causes inducing damage shows necessity to consider $0.5T_m$ damage criterion because of strong current influence on the damage processes. Possible damage mechanisms are described and crack tips motion simultaneously with switching from superconducting to normal state is considered. Application of optically illuminated YBaCuO tapes with nanosecond duration current pulses on the base of the described mechanisms is proposed.

PACS: 74.25.F−, 74.25.fc, 74.25.Op, 85.25.Am

1. Introduction

One of the serious tasks arising against developers of superconducting systems exploiting high density currents is the design of working regimes with prevention of superconducting state breakdown induced by the Joule heating or magnetic field [1]. Another important field of tasks is increase of reliability and lifetime of superconducting devices working in regimes of repeated fast S–N switching (transition from superconducting S state to normal N state), for example in opto-electronic generators of high voltage electrical pulses where thin films are used [2].

Unexpectedly perfect tapes were irreversibly damaged when I slightly exceeded I_c. Another type of damage or irreversible damage of tapes occurred after optical illumination at higher laser fluences. In this report, a model of YBaCuO tape heating during optically initiated S–N switching is introduced. We try to analyze causes when the tape properties degrade or its irreversible damage occurs depending on the current strength as well as on the laser pulse fluence value.

We propose possible application of the investigated regimes causing damage and irreversible damage of the tapes.

2. High-T_c superconducting YBaCuO tapes

During experiment [2] YBaCuO tapes fabricated by laser ablation technique on MgO and $NdGaO_3$ substrates were used. Critical temperature T_c of the tapes was in 85–93 K range. They were of 8–12 mm length l, 3–5 mm width w and thickness d of 0.12–0.6 μm. At the ends tapes have Ag contacts and were placed in parallel to a 50 Ω microstrip line. Critical current density up to 8×10^6 A/cm^2 was measured using nanosecond electrical pulse technique. For illumination laser pulse of 1.06 μm wavelength and 400 ps duration was used. The tapes up to 0.4 μm were fast switched by optical pulse. $Hg_{0.8}Cd_{0.2}Te$ photodiodes were prepared by arsenic diffusion from the vapor source into n-type single crystal substrates followed by annealing process under Hg-saturation condition ($n \approx 1 \div 6 \times 10^{15}$ cm^{-3} at 77 K).

3. Current density at effective penetration depth of the tape

In the critical state and in the regime $I > I_c$, current is homogeneously distributed across the tape. When $I < I_c$, current is quasi-homogeneously distributed through the tape cross-section and current density at the edges of the tape is higher [3, 4]. Let us assume that λ_L, the London penetration depth, temperature dependence is

$$\lambda_L(t) = \lambda_L(0)/\sqrt{1-t^\gamma}\,, \tag{3.1}$$

where $t = T/T_c$ and γ is parameter depending on quality of a tape. For the "high" quality tapes $\lambda_L(0)$ is less than 160 nm and γ exceeds 1.8. For a tape of width w and thickness d effective penetration depth λ_{eff} is [4]:

$$\lambda_{eff}(t) = 2\lambda_L^2(t)/d\,, \tag{3.2}$$

and current density at λ_{eff} is defined by

$$j_\lambda(t) = \left(\frac{\sqrt{2}}{\pi}\right)\left(\frac{I}{\sqrt{wd}}\right)\left(\frac{\sqrt{1-t^\gamma}}{\lambda_L(0)}\right). \tag{3.3}$$

In our calculations, we assume that tapes have following parameters: width 4 mm, thickness 120 and 300 nm, T_c = 90 K and are placed at ambient temperature T = 77 K. For "high" quality tapes $\lambda_L(0)$ is set 150 nm and γ is set 1.8. For "low" quality ones $\lambda_L(0)$ is set 300 nm and γ is set 1.5. For the "high" tapes λ_{eff} is found to be

1.53 μm and 612.7 nm, and for the "low" quality tapes $\lambda_{\rm eff}$ is found to be 7.2 μm and 2.87 μm for corresponding thicknesses. The calculation results (Fig. 1) show that current densities at $\lambda_{\rm eff}$ by 20–50 times exceed average current density calculated as $I/(wd)$.

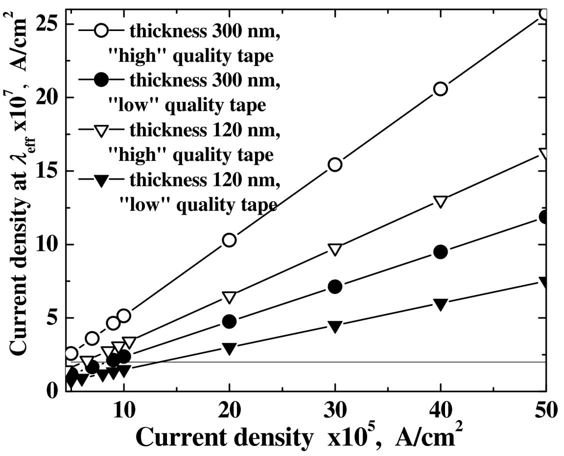

Fig. 1. Current density at $\lambda_{\rm eff}$ vs. current density calculated by $I/(wd)$. Horizontal line corresponds to the density when $j_{\rm c} \approx j_{\rm d}$ for "high" quality tapes.

4. Model of YBaCuO tape heating initiated by optical pulse

Relatively short optical pulse $\tau \approx 400$ ps divides long 15 ns electric pulse into two parts: $t_1 = 5$ ns, when the tape is S state or in mixed state, depending on current value, and $t_2 = 10$ ns, when the tape is switched to N state by optical pulse. For the wide tapes resistance in N state is 15–20 Ω, which is lower compared with 50 Ω wave resistance of the transmission line and therefore the current in the second part becomes approximately by 30% lower than before the optical pulse. The small increase of tape resistance in the mixed state was not taken into consideration.

During the first part of electrical pulse the tape temperature is not changed. It increases during action of the optical pulse. From the energy conservation law this increase is expressed as

$$\Delta T_{\rm opt} \approx \Psi \sqrt{a/\pi\tau}/\chi\,, \tag{4.1}$$

where Ψ is optical pulse fluence; $a = 0.28 \times 10^{-5}$ m^2/s is temperature conductivity and $\chi = 5$ W/(m K) at 100 K is heat conductivity of YBaCuO. This temperature increase influences tape resistance in the second part. We assume that the tape resistivity $\rho_{\rm el}$ increases linearly with temperature increase

$$\rho_{\rm el} = \rho_{\rm el0}\left(1 + \alpha_\rho \Delta T_{\rm opt}\right)\,, \tag{4.2}$$

where $\rho_{\rm el0} = 3 \times 10^{-6}$ Ω m at 100 K is resistivity and $\alpha_\rho = 3 \times 10^{-2}$ 1/K is temperature coefficient of resistivity of YBaCuO.

The tape temperature at the end of the second part can be found from formula

$$T_{\rm el} = j^2 \rho_{\rm el} t_2/c\rho\,. \tag{4.3}$$

Here j is current density after the optical pulse, $c = 200$ J/(kg K) at 100 K is specific heat and $\rho = 6.3 \times 10^3$ kg/m^3 is density of YBaCuO.

Strains in the tapes appear during optically induced S–N switching. The microcracks and cracks open when the temperature increase exceeds half of the melting temperature $T_{\rm m} = 1280$ K ($0.5T_{\rm m}$ criterion). The strain value in the film is defined by formula

$$\sigma \approx \alpha_l G T/(1-\mu)\,, \tag{4.4}$$

where $\alpha_l = 8 \times 10^{-6}$ 1/K at 100 K is linear expansion coefficient, $G = 42 \times 10^{-9}$ is volume shear modulus, and $\mu = 0.264$ is the Poisson coefficient of YBaCuO. Calculation shows that according to the criterion, the cracks will open when the strain value reaches $\sigma \approx 2.9 \times 10^8$ N/m^2.

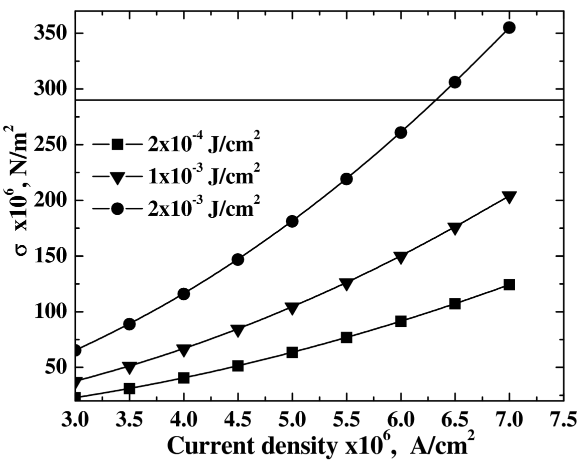

Fig. 2. Strain values vs. average current density in the tapes depending on laser pulse fluence. Horizontal line corresponds to opening of the cracks using $0.5T_{\rm m}$ criterion.

Strain values versus an average current density in the tape are shown in Fig. 2. Opening of cracks, and correspondingly irreversible damage, may be reached at relatively high values of the current densities and optical pulse fluences.

5. Discussion of results

As we can see in Fig. 1, when average current density is above 10^6 A/cm^2, the density at $\lambda_{\rm eff}$ exceeds value $\approx 2 \times 10^7$ A/cm^2, and it corresponds to the condition $I_{\rm c} \approx I_{\rm d}$ for perfect films [5]. Quasi-homogeneous current distribution contributes to formation of edge barriers with bending current lines and offer resistance to entry of vortexes [6]. Fast (nanosecond) current growth, and corresponding magnetic field favour local S–N switching at the bending place even when I is slightly above than $I_{\rm c}$.

Most probably the increased current density at λ_{eff} remains unchanged during fast S–N switching and at the places of bendings not only breakdown of S state, but also damage or irreversible damage of the tapes can occur. This is a possible explanation why the difference $j_{\text{d}} - j_{\text{c}}$ goes to zero for perfect thin films [5] and they therefore are not suitable for repeated S–N switching.

Strain values versus current density in the tape are shown in Fig. 2, where plotted data obtained by our model at different optical pulse fluences. The crack appearing criterion (using Eq. (4.4)) is defined for the materials without flowing current. Presence of a current after S–N switching will lower the obtained strain value. Moreover cuprate oxides have a perovskite structure, where strong electron–lattice coupling exists [7]. At lower strain values, before the opening of cracks, repeated S–N switching with heat up the tape can initiate diffusionless structural transformations (martensitic type transformations), which cause film damage and, as a result, lowers T_{c} and j_{c} values transforming "high" quality tapes to the "low" quality ones. Our calculation model does not involve the above considerations. Experimental verification of strain value range, depending on current densities and laser pulse fluences is needed.

Relatively low heat conductivity and high resistivity of YBaCuO in N state and current concentration at crack tips can develop uncontrolled temperature growth at the tips and their motion with high velocities — so-called dissipative instability [8]. Situation when the crack tip moves simultaneously with S–N switching is worth noting. Velocity of the propagation v_n can be estimated as $v_n \approx \lambda_{\text{eff}}/\tau_0$, where τ_0 is time of temperature growth in volume $\lambda_{\text{eff}}^2 d$. Effect of tip movement simultaneously with S–N switching favor "high" quality films.

Let us consider a limiting case of heating to T_{m} in adiabatic regime of a "high" quality tape ($d = 120$ nm and $\lambda_{\text{eff}} = 1532$ nm). If at the tip, in the volume $\lambda_{\text{eff}}^2 d$, the current is concentrated up to density of $j = 10^7$ A/cm^2 and an adiabatic temperature growth (examining the limiting case with exploring formula (5)) in the volume occurs up to 1280 K during $\tau_0 \approx 7.3\times10^{-9}$ s, and supposing average $\rho = \rho_{\text{el}}$ (YBaCuO, T_{room}) the estimated tip velocity is $v_n \approx 210$ m/s.

If at the same conditions S–N switching and the temperature growth in $\lambda_{\text{eff}}^2 d$ occurs during $\tau_0 \approx 1.5\times10^{-9}$ s, supposing average $\rho = 5\rho_{\text{el}}$ (YBaCuO, T_{room}), the estimated velocity is $v_n \approx 10^3$ m/s, and is close to the Rayleigh velocity ($\approx 1.5\times10^3$ m/s). Reaching to these velocities causes crack branching effect during the movement [9]. Temperature at crack tip faster increases up to T_{m} due to branching.

If at the same conditions S–N with switching and the temperature growth in $\lambda_{\text{eff}}^2 d$ occurs during $\tau_0 \approx 1.5\times10^{-10}$ s (some more than pure S–N switching time) and supposing increased average $\rho = 50\rho_{\text{el}}$ (YBaCuO, T_{room}) the estimated velocity is $v_n \approx 10.3\times10^3$ m/s and is detonation wave velocity. Energy dissipation in these cases is $\approx 1.5\times10^3$ J/cm^3, which is close to the detonation regime ($\approx 2\times10^3$ J/cm^3). This situation is very close to detonation regime of N zone propagation, which was predicted in [10].

6. Conclusions

In conclusion we propose some applications of damage regimes with optically illuminated tapes. Current concentration effect exists near the edges of a "high" quality tape in S state with $I < I_{\text{c}}$. If a centered laser pulse of diameter smaller than $w - 2\lambda_{\text{eff}}$ and of low fluence (about 2×10^{-4} J/cm^2) is used for S–N switching, it does not cause any tape damage at illuminated area, but strengthens current concentration near the edges. Therefore near the edges, close to illuminated area, the tape will be converted from "high" quality tape to a "low" one. In such a transformed tape, the current concentration effect becomes indistinct and j_{c} becomes lower, but the difference $j_{\text{d}} - j_{\text{c}}$ gets larger. Thus, the tapes are suitable for repeated optical switching.

If $I > I_{\text{c}}$, then the centered laser pulse of diameter above $w/2$ and of high fluence (about 2×10^{-3} J/cm^2) induces irreversible damage in the tape center. High density current flows around the damaged place. Fast movement of crack tips perpendicularly to the current lines with simultaneous S–N switching causes current cut-off. This irreversible damage can find application in design of high power single superconducting opening switches.

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