Laser-induced modification of transport properties of Y–Ba–Cu–O step-edge weak links

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We report on the laser-induced permanent changes of the critical current ($I_c$) and normal resistance ($R_n$) of $\text{YBa}_2\text{Cu}_3\text{O}_7-x$ (YBCO) step-edge Josephson junctions. The 2- to 20-µm-wide junctions were prepared from a 200-nm-thick YBCO film deposited by a pulsed KrF excimer laser onto 300-nm-high steps etched in the LaAlO$_3$ substrate. The laser modification experiments were performed by illuminating the junctions at 50 K with a focused Ar-ion laser beam of various intensities. Depending on the illumination power density, either increase or decrease of the junction $I_c$ has been observed. In particular, after illumination at the $0.6\times10^5$ W/cm$^2$ power level, a 75% enhancement of $I_c$ and increase of the $I_cR_n$ product up to 25% were obtained without a measurable change in the junction critical temperature. The laser-induced modifications were very reproducible and remained unchanged even after a subsequent room-temperature/helium thermal cycling of the sample. Photoassisted, thermally activated oxygen redistribution in the YBCO grain boundary region is proposed to explain the observed behavior.

Step-edge weak links based on $\text{YBa}_2\text{Cu}_3\text{O}_x$ (YBCO) superconducting films emerge as a promising basic element for high-temperature superconducting electronics. The step-edge junctions are relatively easy to fabricate, and their properties were shown to be tunable, e.g., by varying the step height and angle and/or the ratio of the step height to the YBCO film thickness. Large-scale fabrication of reproducible step-edge junctions (i.e., with predefined, desired properties and a low spread of parameters), a feature that is necessary for any circuit applications, is the main current technological concern.

A new approach to YBCO junction engineering was recently proposed by Tanabe et al., who demonstrated the possibility of adjusting parameters of already fabricated bicrystal and step-edge weak links by low-power laser irradiation. In the above work, the observed, light-induced changes of junction parameters were ascribed to photoinduced hole doping of an oxygen-deficient YBCO grain-boundary area. Those findings are consistent with the earlier data, showing that prolonged, low-power light illumination of partially oxygen-depleted YBCO films results in a gradual decrease of their resistivity and an enhancement of the material superconducting transition temperature. However, the photoinduced changes, though persistent under 250 K, relax back to equilibrium at higher temperatures, making application of this method for practical (i.e., permanent) adjustment of the junctions’ parameters rather limited.

Simultaneously, medium-to high-power laser irradiation was shown to locally control oxygen diffusion in or out of the sample (depending on the sample ambient atmosphere) in YBCO thin films. This technique was applied for precise formation of oxygen-rich and/or oxygen-deficient areas in YBCO films and YBCO–SrTiO$_3$ structures. In addition to changes in oxygen content, a significant oxygen redistribution within the YBCO crystalline structure was observed under the laser irradiation.

The aim of this letter is to demonstrate that laser-induced oxygen redistribution and outdiffusion introduce desirable changes in the parameters of YBCO step-edge weak links. Contrary to the photodoping effect, medium- to high-power laser modifications of the junctions’ transport properties are permanent, in a sense that they can withstand room-temperature/helium thermal cycles and can be erased only via the high-temperature heat treatment. The laser-modification process, developed by us, leads to the increase of the junction critical-current normal-state-resistance product ($I_cR_n$), while still preserving the sample’s overall characteristics of a resistively shunted junction (RSJ).

Our step-edge weak links were formed on the LaAlO$_3$ substrates. To produce the steps in a LaAlO$_3$ crystal, a 150-nm-thick Nb film was first deposited onto its surface. The film was then photolithographically patterned and reactive ion etched with CF$_4$. After removing the photoresist, the sample was Ar-milled at a rate of 4 nm/min to form 300-nm-high steps in LaAlO$_3$. During the Ar milling, the substrates were attached to the water-cooled stage at an angle of 90° with respect to the ion beam. Each substrate was subsequently stripped of the remaining Nb, and a 200-µm YBCO film was deposited by a KrF excimer laser. Afterward, 2- to 20-µm-wide junctions were photolithographically patterned across the step edges using ion milling in 2.6×10$^{-2}$ Pa of Ar. A lift-off technique and oxygen annealing at 400 °C were...
We found that, depending on the sample, the critical temperature \( T_c \) of our junctions varied between 85 and 89 K and the junction current–voltage \( I_c \) characteristics were registered.

The temperature dependence of the junction’s resistance \( R_c \) was recorded during the slow cooling of the samples. We see that although laser illumination resulted in the decrease of \( I_c \), after the laser processing from 1.1 mV to approximately 5- to 20-m wide microstrip containing no weak links, \( I_c \) enhancement was reproducible and permanent. Once induced, it remained in subsequent measurements, even after room-temperature thermal cycling of the junction. A further increase of \( P_L \) led to a significant drop of \( I_c \), after the laser treatment led to the overall increase of the junction \( I_c \) at very low values of \( P_L \), due to the photodoping effect. For higher \( P_L \), a considerable increase of \( I_c \), up to 75\% for the 2-m junction and 45\% for the 20-m junction was observed. The effect occurred in a relatively narrow power interval and exhibited a well-defined threshold, approximately the same for all tested junctions. The \( I_c \) enhancement was reproducible and permanent. Once induced, it remained in subsequent measurements, even after room-temperature thermal cycling of the junction. A further increase of \( P_L \) led to a significant drop of \( I_c \) in our junctions [Figs. 1(a) and 1(b)], in a manner similar to that measured in the microstrip [Fig. 1(c)], where no illumination-induced increase of \( I_c \) was observed. In this latter case, we simply registered a substantial decrease of \( I_c \), after the \( P_L \) of approximately 0.9 \times 10^5 W/cm^2 was exceeded.

Figure 1 shows the \( I_c \) dependence on the illumination power density \( P_L \) for 2-m wide [Fig. 1(a)] and 20-m wide [Fig. 1(b)] step-edge weak links, as well as for a 20-m wide microstrip containing no weak links [Fig. 1(c)]. For \( P_L \) lower than 0.6 \times 10^5 W/cm^2, no change in transport properties of the junctions nor the microstrip was detected, besides a small (not shown) increase of the junction \( I_c \) at very low values of \( P_L \). For higher \( P_L \), a significant increase of \( I_c \), up to 75\% for the 2-m junction and 45\% for the 20-m junction was observed. The effect occurred in a relatively narrow power interval and exhibited a well-defined threshold, approximately the same for all tested junctions. The \( I_c \) enhancement was reproducible and permanent. Once induced, it remained in subsequent measurements, even after room-temperature thermal cycling of the junction. A further increase of \( P_L \) led to a significant drop of \( I_c \), after the laser treatment led to the overall increase of the junction \( I_c \) at very low values of \( P_L \), due to the photodoping effect. For higher \( P_L \), a considerable increase of \( I_c \), up to 75\% for the 2-m junction and 45\% for the 20-m junction was observed. The effect occurred in a relatively narrow power interval and exhibited a well-defined threshold, approximately the same for all tested junctions. The \( I_c \) enhancement was reproducible and permanent. Once induced, it remained in subsequent measurements, even after room-temperature thermal cycling of the junction. A further increase of \( P_L \) led to a significant drop of \( I_c \), after the laser treatment led to the overall increase of the junction \( I_c \) at very low values of \( P_L \). Thus, our laser treatment led to the overall increase of the junction \( I_cR_n \) product. For the 2-m junction, the \( I_cR_n \) at 50 K increased after the laser processing from 1.1 mV (curve a) to
For medium consistent modifications of the junctions’ transport properties. Therefore, only oxygen rearrangement and/or removal can be considered as the two possible processes leading to per-

vacuum, so there was no oxygen diffusion into the sample.

Our illumination experiments were performed in

Figure 3 shows the $R$–$T$ dependencies of the 20-μm junction before illumination (curve a) and after the laser-induced suppression of $I_c$ (curve b). Curve b shows a $T_c$ decrease and transition broadening, both typical for oxygen-deficient YBCO. We stress that laser treatment leading to the oxygen outdiffusion from YBCO at high $P_L$ levels is, according to our findings, related to thermally induced outdiffusion of oxygen from the junction electrodes. We believe that our laser modification technique can be a suitable tool for fine adjustment of junction parameters (e.g., reduction of the $I_c$ spread) in YBCO Josephson circuits.

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with a potential barrier more conducting ($R_n$ decrease). The overall quality of the junction is improved, as is indicated by the increase of the $I_c R_n$ product. High-intensity laser illumination clearly leads to the oxygen outdiffusion. This observation is also supported by the fact that the high-illumination effects observed for the junctions were essentially the same as those for the microstrip, showing that, in this case, oxygen was removed also from the entire structure.

In summary, permanent laser modification of transport properties of YBCO step-edge weak links has been demonstrated. Both increase and decrease of the junction $I_c$, depending on the laser illumination power density, were obtained. The changes remained stable after room-temperature thermal cycling of our junctions and could be erased only by the high-temperature annealing of the sample in an oxygen atmosphere. The observed increase of the junction $I_c R_n$ product can be explained by photoassisted thermal oxygen reordering within the YBCO grain-boundary region, while the $I_c$ decrease at high $P_L$ levels is, according to our findings, related to thermally induced outdiffusion of oxygen from the junction electrodes. We believe that our laser modification technique can be a suitable tool for fine adjustment of junction parameters (e.g., reduction of the $I_c$ spread) in YBCO Josephson circuits.

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