High critical current density and scaling of phase-slip processes in YBaCuO nanowires

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Abstract

YBaCuO nanowires were reproducibly fabricated down to widths of 50 nm. A Au/Ti cap layer on YBCO yielded high electrical performance up to temperatures above 80 K in single nanowires. Critical current density of tens of MA cm\textsuperscript{−2} at \(T = 4.2\) K and of 10 MA cm\textsuperscript{−2} at 77 K were achieved that survive in high magnetic fields. Phase-slip processes were tuned by choosing the size of the nanochannels and the intensity of the applied external magnetic field. Data indicate that YBCO nanowires are a rather attractive system for the fabrication of efficient sensors, supporting the notion of futuristic THz devices.

1. Introduction

Superconducting nanostructures operating at liquid nitrogen temperature are very attractive for several applications in superconducting electronics. In particular high critical temperature superconductor (HTS) nanowires not only have the advantage of high temperature operation, but in principle can be functionally scaled to smaller sizes \cite{1, 2} due to their extremely short coherence lengths \(\xi_0\). Other intrinsic properties of these materials can play a relevant role too. For instance, their characteristic fast relaxation times \cite{3} offer higher counting rates in photodetection experiments when compared to traditional superconductors \cite{4}.

In this context reliable top-down fabrication techniques allowing a more direct integration of the HTS nanostructures into hybrid systems are of much interest. Here we analyze the electrical properties of a number of nano-fabricated wires down to 50 nm in width. Our measurements show very good performance for single YBCO nanowires both in terms of critical temperature \(T_C\) and critical current density \(J_C\) with excellent potential for sensor applications. Critical current densities up to 70 MA cm\textsuperscript{−2} at \(T = 4.2\) K and 10 MA cm\textsuperscript{−2} at 77 K were achieved on YBCO capped by a thin protective layer of Au/Ti. These are among the best results reported for single nanowires \cite{5–8} (see below). Contrary to other works \cite{2}, where even smaller sizes were achieved for arrays of nanowires, in this case we isolated single nanowires, thus responding to a much wider range of requirements for circuit design.

2. Experimental details

We have employed YBCO thin films produced on various substrates through different deposition techniques (sputtering and reactive thermal co-evaporation \cite{9}). For the aims of this work of demonstrating a reliable top-down technology to obtain single YBCO nanowires down to a width of 50 nm and the utility of using a Au cap layer, the desirable properties of the thin films are rms roughness as low as possible and the absence of macroscopic impurities in the film. The initial values of \(T_C\) and \(J_C\) of unpatterned films are relevant but not crucial. In order to perform systematic experiments and reliably compare nanostructures realized on different samples, we have employed thin films produced on...
large areas by the co-evaporation technique of Theva [11]. From the same wafer, it is possible to cut 20 samples of size 5 mm × 5 mm with the same properties. In this work we focus on c-axis YBCO thin films (50 nm thick), grown on a CeO$_2$ seed layer (40 nm thick), and protected by a 20 nm thick Au layer [11]. The substrate is a large wafer of yttria-stabilized zirconia (YSZ). The values of the original critical temperature and of the critical current density are high ($T_C \approx 86.5$ K and $J_C = 2.2$ MA cm$^{-2}$ at $T = 77$ K) but not optimized to the highest possible values. The key-steps of the nanotechnology approach are based on the use of a 30 nm thick Ti mask patterned through e-beam lithography (Zeiss MERLIN), and on a low energy milling procedure keeping the sample at a temperature of about $-150$ °C. Most of the procedure is described in detail in [12]. All nanobridges described in this work are $1 \mu$m long. A comparative study of bare and capped YBCO nanowires on samples produced in the same deposition run and only differing by the last fabrication step (bare nanowires undergo an additional ion milling step in order to remove the Au layer) sheds light on the role of the Au layer protecting the nanowires. The Au/Ti layer makes the integration of the YBCO component into hybrid structures easier because of its better compatibility with other materials as opposed to HTS. If only genuine superconducting properties are required, the YBCO capped nanowires can perfectly replace YBCO nanowires for most functions. Nano-fabrication techniques are not restricted, for the resolutions specified above, to any specific choice of the substrates usually employed for HTS thin films, or thin film deposition conditions, as long as surface roughness is below some thresholds, for instance lower than 5 nm on a total thickness of 50 nm. This approach can be extended to produce junctions and more complicated structures [13].

Measurements were performed in liquid helium using a four-probe configuration. The set-up employed is equipped with two stages of cold filters (copper powder and RC Pi filters with a cut-off frequency of the order of a few GHz and 160 MHz respectively).

3. Results and discussions

The critical temperature of various representative devices is reported as a function of wire width in the inset of figure 1. $T_C$ scales linearly for both types of bridges. For the capped YBCO nanowires is basically the same as the unpatterned films and reaches about 85 (78) K for nanowires of $w = 160$ nm. Superconductivity is quite robust also for widths less than 200 nm, but the properties of devices are less reproducible.

Not surprisingly, the bare YBCO thin films are more sensitive to ion milling and processing details. Figure 1 shows resistance versus temperature curves for the capped YBCO nanowires. Both bare and capped YBCO data can be well fitted in terms of the thermally activated phase-slip model, i.e. the Langer–Ambegaokar–McCumber–Halperin (LAMH) model [14] commonly used to describe the broadening of $R(T)$ in superconducting nanostructures [15]. The total resistance of the wire is commonly expressed as the parallel [15] between the resistance activated by phase-slip processes $R_{LAMH}$

$$R_{LAMH} = R_Q \frac{h \Omega}{k_B T} \exp \left( \frac{\Delta F}{k_B T} \right)$$

and the normal resistance of quasiparticles $R_N(T) = R_N \exp(-\Delta F(T)/k_B T)$ [16]: $R(T)^{-1} = R_{LAMH}(T)^{-1} + R_N^{-1}(T)$. Here $\Omega = (L/\xi) \sqrt{(\Delta F/k_B T)}(1/\tau_{GL})$ is the phase slipping rate, $\tau_{GL} = (\pi h/\xi_B (T_C - T)$), $R_Q = h/4e^2$ is the quantum resistance constant, $L$ is the sample length, $\xi_B$ is the Boltzmann constant, and $\Delta F$ is the free energy where the superconducting phase ‘falls off’. $\Delta F$ at $T = 0$ K can be expressed as $8\sqrt{2}/(48\pi^2)e^2 LAMH\lambda \xi_B$ where $A$ and $\lambda$ are the cross section and the London penetration depth respectively) in analogy with other experiments on HTS nanowires [2]. The extracted values of the fitting parameters are $\xi_0 \sim 2$ nm and $\lambda \sim 300$ nm, which are quite consistent with typical values for cuprates [10]. $\Delta F$ is for all curves about $10^5$ K.

Measured critical current density values are reported as a function of the width ($w$) for $T = 4.2$ K in figure 2 and compared with results available in literature [5–8]. $J_C$ in capped YBCO nanowires is higher than 30 MA cm$^{-2}$ (for $w = 50$ nm) and reaches a maximum of 70 MA cm$^{-2}$ for $w = 140$ nm. These are among the highest values reported [5–8] and only a few times lower than the theoretical depairing limit (300 MA cm$^{-2}$) [17]. $J_C$ values at $T = 77$ K are reported in figure 2 inset (a) for YBCO/Au/Ti nanowires and range from 2 MA cm$^{-2}$ for $w = 50$ nm to 20 MA cm$^{-2}$ for $w = 140$ nm. The better performance offered by capped nanowires when compared with that of bare YBCO nanowires in this and previous works [6] reveals that the protecting Au layer is key for enhancing the quality of HTS nanowires. We believe
Figure 2. Values of critical current density $J_C$ measured at 4.2 K versus channel width ($w$). Data from this work (gray circles for YBCO nanowires, black circles for YBCO/Au/Ti nanowires) are compared with results available in the literature [5–8]. UV stands for the increase of $J_C$ obtained by ozone treatment [7]. Inset (a) $J_C$ versus $w$ of the YBCO/Au/Ti nanowires measured at 77 K are compared with [6]. Inset (b) $J_C$ of the 50 nm wide nanochannel (measured at $T = 4.2$ K) at different values of the magnetic field $H$ are compared with typical data from the literature [18].

that there are margins to further improve $J_C$ performance, especially at 77 K, by employing films with higher values of the initial $T_C$.

Nanowires also have good transport properties when an external magnetic field is applied. For instance, in the extreme limit of 50 nm, a magnetic field of 10 T reduces $T_C$ by less than 10%, while $J_C$ at 4.2 K is only halved. Superconductivity in 50 nm wide strips survives up to $H = 1$ T at 77 K. Figure 2 inset (b) allows a comparison of the dependence of $J_C$ on magnetic field at $T = 4.2$ K [18] in the present samples with other results and confirms the robustness against an externally applied magnetic field. The use of HTS for power applications is a field of research of great relevance and a ‘smart’ control of pinning centers is key to increase $J_C$. In macroscopic samples this role is usually played by the introduction of nanodefects [19, 20], while in nanowires by the detailed structure of the edge barrier [21].

Figure 3(a) shows the experimental current–voltage ($I$–$V$) characteristics measured at $T = 4.2$ K for YBCO/Au/Ti nanowires 130, 80 and 50 nm wide. The distinctive feature is the presence of steps accompanied by a very large hysteresis that exceeds 30% of the total current. Similar features were reported by several authors in experiments employing nanostructures (a large collection is reported in [15]) and HTS nanowires [2, 23–25]. These observations were interpreted in terms of phenomena driving the superconducting channel to the normal state, i.e. the development of phase-slip centers (PSCs) or normal hot spots (HPs) [26]. Because of their low carrier density and thus low superfluid rigidity, HTS systems are inherently prone to phase fluctuations and therefore more susceptible to PSCs in reduced dimensions [22, 15]. $I$–$V$ curves reported in figure 3 show that the amplitude and the position of the steps depends on the size of the nanochannels and on the magnetic field. By increasing the width of the channel, the switch occurs at higher voltage. This is consistent with the idea that in wider samples the transition to the fast vortex motion that leads to the step structure occurs at a larger current [29]. As shown in figure 3(b), an increase in $H$ moves $V_{1on}$ to higher voltages to a maximum of about 15 mV for $H = 10$ T. The voltage jump $\Delta_{SW}$ is also reduced from $\Delta_{SW} = 80$ mV at $H = 0$ T to about 10 mV at $H = 10$ T.

From the value of the critical voltage $V_{1on} = v_C H L$ [27, 29] it is possible to estimate the vortex critical velocity $v_C = 10^2$ m s$^{-1}$ (at $H = 1$ T), and, as a consequence, the inelastic electron–electron scattering time is $\tau_S \approx 0.6$ ns derived from the expression $\tau_S = D [14 \zeta(3) \gamma^{0.5} (1 - T/T_C)^{0.5} / \pi v_C^2]^{0.5}$, where $D$ is the quasiparticle diffusion constant and $\zeta(3) \approx 1.2$. This value is in agreement with other experiments [28] and estimates [29].

The scaling of the $I$–$V$ curves and of the steps with the width of the nanochannels and the influence of $H$ on the $I$–$V$ curves reflects the presence of phase-slip lines (PSLs) [30, 29]. PSLs are a two-dimensional analog of PSCs and reveal some kind of phase transition in the vortex lattice.
at the instability point with regions of fast and slow vortex motion [30, 29]. When the width of the bridges is reduced to \( w = 50 \text{ nm} \), the step position \( (V_{\text{ion}} = 0) \) and the shape of the \( I-V \) curve indicate a transition from PSL to the more classical one-dimensional PSC (at \( H = 0 \text{ T} \)). In the narrowest nanowire, not more than one line of vortices at low fields can be hosted. When the magnetic field is increased, the size of inter-vortex distance \( a = \sqrt{\Phi_0 / H} \) is decreased (for instance \( a = 20 \text{ nm} \) at \( H = 5 \text{ T} \)), and the entrance of additional rows of vortices is favored, with a consequent transition to PSL. This is documented by the steps at finite voltage in the presence of magnetic field \( (V_{\text{ion}} > 0) \). Vortex motion is characterized by oscillatory behavior of flux lines which cross the sample, resulting in an emission of electromagnetic radiation \( v = v_c / a \) that, for instance, is on the order of \( 0.2 \times 10^{11} \text{ Hz} \) at \( H = 1 \text{ T} \).

Studies on the dynamics of kinematic vortex–antivortex lines confirm that their individual velocity can be manipulated by applying magnetic field and current [31], supporting the notion of futuristic THz devices.

4. Conclusions

In conclusion, single YBCO nanowires were fabricated through an Au/Ti cap layer to reach very high values of the critical current density also at 77 K that is very robust against an externally applied magnetic field \( H \). The detailed structures of the \( I-V \) curves of these single nanowires can be tuned by choosing the size of the bridge and by setting the magnetic field intensity. Threshold mechanisms associated with phase slip processes and visible as steps in the \( I-V \) curves pave the way to HTS nanowires as sensors for photodetection experiments.

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