INSTITUTE OF PHYSICS PUBLISHING SUPERCONDUCTOR SCIENCE AND TECHNOLOGY

Supercond. Sci. Technol. **17** (2004) 438–442 PII: S0953-2048(04)68928-7

Junctions formed in $YBa_2Cu_3O_{7-\delta}$ nanowires

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Received 9 September 2003, in final form 22 November 2003
Published 20 January 2004
Online at stacks.iop.org/SUST/17/438 (DOI: 10.1088/0953-2048/17/3/023)

Abstract

We report the fabrication and characterization of $YBa_2Cu_3O_{7-\delta}$ nanowires with various kinds of junctions, including Dayem bridges, crossed junctions and S–I–S junction arrays. Ideal flux pinning centres were introduced into these nanowires and the ceramic nanowires were found to have potential plasticities favourable for nanoscale processing. Prospective physical properties and superconducting nanoelectronic applications of these nanowires are expected.

1. Introduction

The breakthrough in nanoscale molecular circuits [1] makes it possible to explore further the superconducting nanoelectronic world. While we accept the low-T_c superconductivity in carbon nanotubes [2–5] and the quantum suppression of superconductivity in ultrathin composite nanowires [6], a question naturally arises: why not develop a nanoscale circuit by using high-T_c superconducting nanowires as the basic components? To date, however, growing one-dimensional (1D) high-T_c ceramic nanowires, especially those with ideal nanoscale Josephson junctions, seems to be difficult, in spite of the fact that centimetre- or micrometre-sized superconducting crystals [7, 8] and composites [9] have been grown and various kinds of Josephson junctions [10–12] have been fabricated through state-of-the-art techniques. In this paper, we report a modified sol–gel method to fabricate $YBa_2Cu_3O_{7-\delta}$ nanowires. Nano-junctions grown through unusual one-dimensional sintering, an ideal nano-pinning system and deformation-induced junctions were characterized by transmission electron microscopy.

2. Experimental procedure

$YBa_2Cu_3O_{7-\delta}$ nanowires were grown in this study through controlled sintering of sol–gel coated and filled carbon nanotubes. Metal nitrates, weighing the stoichiometric molar ratio of around Y:Ba:Cu = 1:2:3, were used as the starting materials for the preparation of sol solutions [13]. Purified multi-walled carbon nanotubes (CNTs) [14] with varying diameters (outer diameter: 10–40 or 70–100 nm) and opened tips (figure 1) were then mixed with the sol. After evaporation at temperatures below 200 °C, the mixture was heated up to 600–700 °C to remove the carbon nanotubes, sintered at 925–945 °C in air and then cooled to room temperature. The powders were ultrasonically dispersed in absolute alcohol and then dropped onto supporting membranes for examination in a transmission electron microscope (JEOL 100CX) and a field emission electron microscope (Philips CM200 FEG). Phase components in the synthesized products were also examined by x-ray diffraction (Rigaku D/MAX III).

3. Results and discussion

X-ray diffraction analyses of the final products revealed that, by serving as an effective grain refiner to refine precursor particles (including sol particles and polycrystalline particles obtained after the low-temperature calcinations of the deposited gels) and thus reducing the formation energy of the final superconducting phases, the carbon nanotube added to the sol–gel system could accelerate the growth of the superconducting phases. By increasing the quantity of carbon nanotubes the number of superconducting phases increased. As shown in figure 2, after 3 h of sintering, 10% wt addition of carbon nanotubes could lead to nearly complete formation of the $YBa_2Cu_3O_{7-\delta}$ (Y123) phase, whereas, in the traditional sol–gel Y–Ba–Cu–O system without the addition of carbon nanotubes, the predominant phase was

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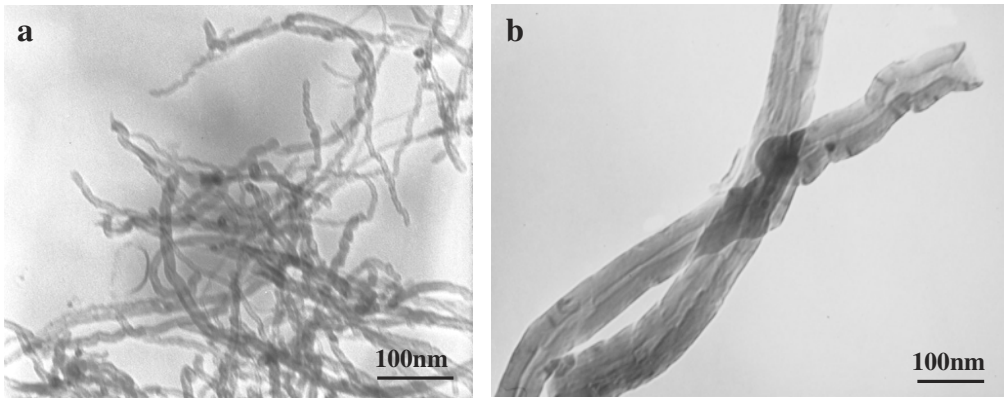

Figure 1. TEM images of purified carbon nanotubes with (a) small diameters and (b) large diameters.

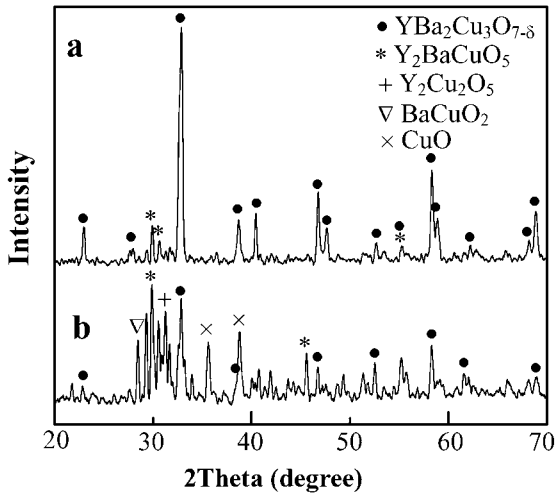

Figure 2. XRD patterns of Y–Ba–Cu–O powders calcined at 945 °C for 3 h. (a) The addition of carbon nanotubes to the precursor solution accelerated the formation of the superconducting $YBa_2Cu_3O_{7-\delta}$ phase. (b) Without the addition of carbon nanotubes the predominant phase was the non-superconducting Y_2BaCuO_5 (211) phase rather than the $YBa_2Cu_3O_{7-\delta}$ phase.

Figure 3. TEM image of as-grown nanowires.

non-superconducting Y_2BaCuO_5 (211 phase) and complete formation of the superconducting phase still needed a much longer transformation time. In addition, decreasing the diameters of the carbon nanotubes could also accelerate the formation of the superconducting phase. As one of the large problems commonly found in fabricating high-T_c superconducting components is a time-costing inefficiency, the result here also suggests that adding carbon nanotubes to the sol solutions should be an efficient way of preparing ultrafine precursor crystals at low temperatures and thus accelerate the sintering and densification of powders to form high quality superconducting materials.

Due to a confined 1D nanospace, the formation of a superconducting nanowire was accompanied with competitive grain growth and sintering along the transverse and longitudinal directions of the nanowire and a moderate sintering densification (shrinkage or coarsening during different stages). Controlling the sintering temperature and time was crucial because rapid grain growth of nanocrystals in the nanowire could occur easily to form highly oriented polycrystalline or single-crystalline structures (as can be verified by our HREM observations of alumina nanowires and Y–Ba–Cu–O- and Bi–Sr–Ca–Cu–O-based nanowires). Y123 oxides in the form of nanowires and nanoparticles were simultaneously found in the synthesized products. The quantity of synthesized Y123 nanowires increased with the increase in carbon nanotubes added to the precursor sol solutions. These nanowires had diameters of several to tens of nanometres and lengths up to several micrometres. They showed either straight or curved shapes (figure 3). Moreover, we could grow quite a few peculiar nanowires with nanostructures that were potential junctions for nanoscale superconducting electronics. These included nanoporous nanowires (figure 4(a)) and crossed nanowires (figure 4(b)) with X or Y shapes induced by high-temperature diffusion bonding similar to that in welding different materials. The weakly linked nanoporous or necked areas in the nanowires could be viewed as special Josephson junctions of Dayem bridges (superconducting nanobridges), as many of these areas could meet the small-size requirement for such kinds of high-T_c junctions [15, 16]. We wonder whether the nanoporous nanowires could possess similar unusual properties to those of the previously reported superconducting foam [17]. The X junction shown in figure 4(b) should be a new crossed junction, which was naturally bonded rather than artificially connected

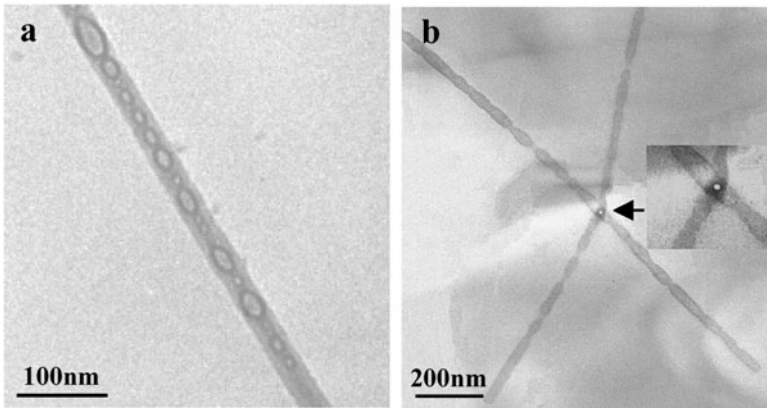

Figure 4. TEM images of the nanowires with special junctions. (a) Regular nanoporous structures induced by preferential surface growth along the longitudinal direction of a nanowire, which contained many Dayem bridges. (b) Crossed junction with a hole in it. The inset is a higher magnification image of the arrowed X junction.

or contacted. The nano-hole in the centre of this junction, which was grown through an unusual atomic diffusion, provides the feasibility of a nano-fixation in superconducting nanoelectronics.

Through the use of ultrafine carbon nanotubes and the composition design of excess insulating phases in the Y–Ba–Cu–O system, ideal flux pinning centres (i.e. non-superconducting 211) could be left in the superconducting nanowires after the formation of the superconducting phases (figure 5). As shown in figure 5(b), non-superconducting particles with very small sizes existed in the superconducting nanowires. The diameter of these non-superconducting particles could be reduced such that it was close to the dimensions of an ideal pinning site, which should be comparable to the flux line core diameter 2ξ (for $YBa_2Cu_3O_{7-\delta}$, 2ξ (0 K) = 3 nm and 2ξ (77 K) = 9 nm) [18]. Thus, an ideal nano-pinning, at least at 77 K, could be expected from these composite nanowires.

Once a regular superconductor/insulator/superconductor (S/I/S) heterostructure (figure 5(c)) formed along the longitudinal direction of the nanowire, 1D arrays of S–I–S junctions could form in the nanowire. By using an ultrafine template and thus decreasing the size of a heterostructure to a certain degree, the thickness of an insulating pinning centre, which occupied the whole cross-sectional area of a nanowire, could be reduced to several nanometres. Then such a small insulating layer would meet the thickness requirement (about 1–3 nm) for a typical S–I–S Josephson junction [19]. We wonder whether any unusual physical properties could be explored in these Josephson junction arrays.

Deformation-induced junctions and nanocrack junctions [20] were also observed because the ceramic nanowires synthesized here showed remarkable plasticity or ability to be deformed before fracture. Figure 6 shows TEM images of several locally deformed and/or fractured nanowires. Although there was the possibility that sintering stress could induce some nanocracks, some of these deformed structures could be induced by external forces caused by ultrasonic vibration of these one-dimensional nanowires before the TEM observation. A close examination of those seemingly fractured surfaces (figure 6(a)) revealed that many of the neighbouring parts were, in fact, weakly connected, similar to the fracture of carbon nano-tubes [21–23] and broken lotus roots with thread-like linkages. As a matter of fact, such a kind of fracture was also found for several precursor nanowires formed under temperatures far below the formation temperature of Y123.

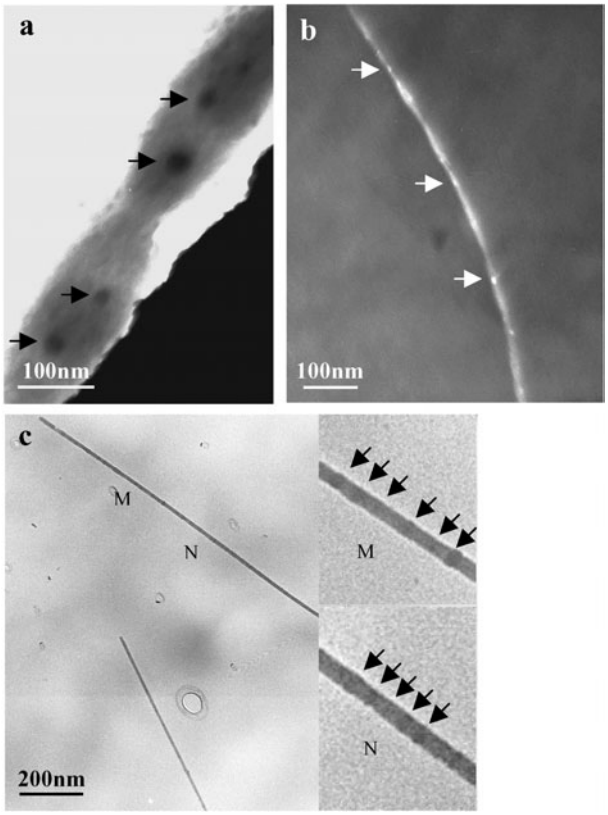

Figure 5. Through composition design and controlled sintering, the superconducting nanowires could be left with insulating or non-superconducting phases. (a) Large flux pinning centres in a coarse nanowire grown with coarse templates. (b) By the use of ultrafine templates we obtained ideal flux pinning centres with dimensions comparable to those of theoretically calculated values (i.e. 9 nm (2ξ) for the Y123 system at 77 K). (c) Nanowires with superconductor–insulator heterostructures. The insets are higher magnification images of the regions M and N shown in the left image. The arrows point towards the insulating components in the one-dimensional S–I–S junction arrays.

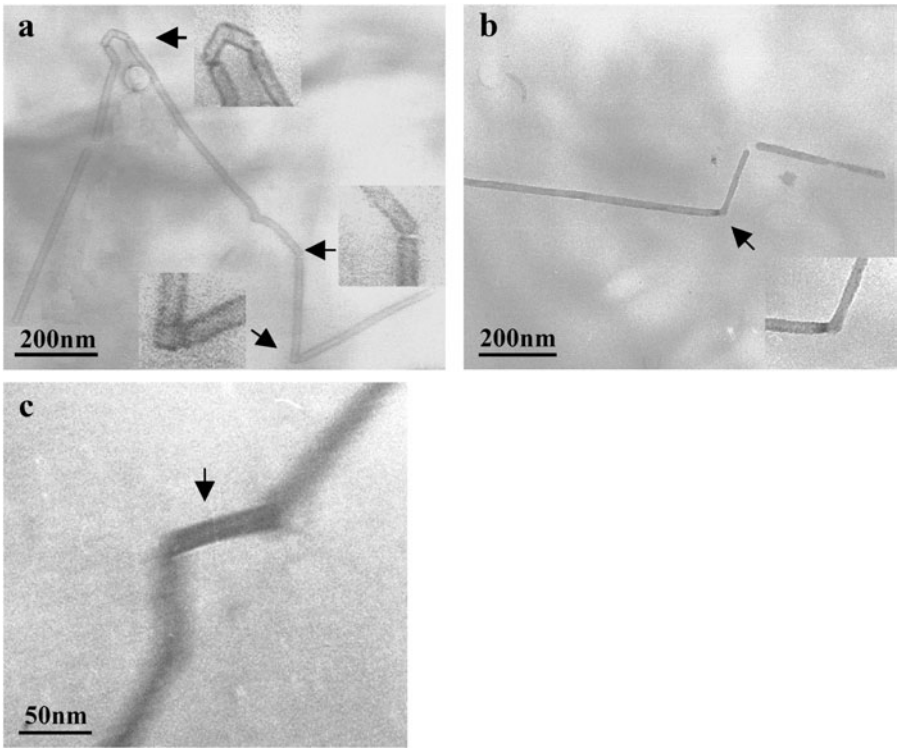

Figure 6. $YBa_2Cu_3O_{7-\delta}$ nanowires showing potential plasticity favourable for nanoscale processing. (a) Nanowire showing several weakly linked or fractured parts. The insets are higher magnification images of the corresponding areas. (b) Locally bent nanowire. (c) Local deformation (arrowed) resulted in different imaging contrasts along the nanowire.

Considering the large strain induced at the deformed and/or fractured surfaces the nanowires presented a better deformation ability than those of the traditional bulk ceramic superconductors. Although the exact mechanism (such as a mechanical response of an anisotropically laminated nanostructure) for these ceramic nanowires to exhibit such high plasticity is yet to be explored, it opens up a large degree of freedom for us to mechanically process these nanowires into favourable shapes (i.e. artificial junctions, kinks and even loops, etc). Building these nanowires as molecular devices would be less hindered than those commonly found in bulk high-T_c ceramic superconductors.

With the availability of these superconducting nanowires, especially those having unusual junctions, we could explore a new fascinating nanoelectronic world. The nanowires are expected to possess anomalous physical properties, including a potentially high critical current density for J_c (due to their highly oriented textures and single-crystalline structures or nano-pinning). We should explore the prospective applications of these nanowires in superconducting molecular devices, such as superconducting nanowires for electronic transportation, superconducting nanotips for scanning tunnelling microscopy [24, 25] and point-contact Josephson junctions [26].

4. Conclusion

In conclusion, we fabricated $YBa_2Cu_3O_{7-\delta}$ nanowires through controlled sintering of sol–gel deposited carbon nanotubes. Due to one-dimensional sintering and deformation various kinds of nanojunctions formed in these nanowires. These nanojunctions and the noteworthy plasticity found in these ceramic nanowires are favourable for applications in superconducting nanoelectronics.

Acknowledgments

This work was supported by the National Fundamental Research Fund and the Outstanding Youth Fund of China.

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