Effect of Si on the superconducting properties of high-T YBCO in bulk and thin film forms

Ahmed Abo-Arais [a] and El-Sayed M. Farag [b]
[a]Physics and Mathematical Eng. Dept., Faculty of Electronic Engineering, Menoufia University, Menouf 32952, Egypt
[b]Basic Science of Eng. Dept., Faculty of Engineering, Shebin El-Kom, Menoufia University, Egypt

The results of Si addition on the superconducting properties of high-T_c YBCO in bulk and thin film forms are reported. The bulk samples are prepared by the solid state reaction method and the thin film of amorphous silicon is deposited by radio frequency glow discharge of silane (SiH_4). The critical temperature of the superconductor (T_c) is decreased with low Si addition. The critical current density (J_c) is reduced by nearly 10^3 in magnitude with Si concentration of x=0.1. The obtained results are explained according to superconductor-semiconductor composite model.

فى هذا البحث تم دراسة تأثير إضافة السليكون على الخواص فائقة التوصيل الكهربى لمركب الأتريوم والباريوم والنحاس فى الحالة الصلبة الحجمية وفى حالة الأفلام الرقيقة. العينات فى الحالة الحجمية تم تحضيرها بواسطة التفاعل فى الحالة الصلبة ولكن العينات فى حالة الأفلام الرقيقة تم ترسيبها بواسطة تردد أشعة الراديو بالتوهج والتفريغ الكهربى لمادة السيلين. درجة التحول للحالة الفائقة التوصيل تقل بإضافة السليكون وكذلك كثافة التيار الحرج يقل بشدة بمقدار حوالي ألف مرة مع نسبة سليكون تساوى ٠,١. تم تفسير النتائج التى حصلنا عليها تبعا لنموذج مركب من المواد فائقة التوصيل والمواد شبه الموصلة.

Keywords: Superconductor YBCO, Semiconductor Si, Superconductor-semiconductor composite model, Transition temperature to superconducting state T_c, Critical current density J_c

1. Introduction

In the last fourteen years much progress has been made in the area of High Temperature Superconductor (HTS) in electronics [1]. Recently HTS multilayer integrated circuit has been built and HTS multichip has been demonstrated [2-4]. There exists an overlap in the temperature range of superconductor and semiconductor applications. Hence, the realization of the proposed superconductor-semiconductor devices that combining the properties of the two materials should be possible [5-10].

The main difficulty in preparing YBCO high-T_c films up on semiconducting material as Si is caused by the interdiffusion due to high substrate temperature during the deposition [5]. To overcome this difficulty, various buffer layers such as ZrO(YSZ); MgO, Y_2O_3 between 50 and 100 nm thick, which prevent the diffusion more successfully used [4]. Although this method provides superconducting films as YBCO on semiconducting substrate as Si, it is not sufficient to realize superconductor-semiconductor devices due to the insulating buffer layer [4]. The buffer layer prevents the direct combination between superconducting and semiconducting materials .

In the present study, results of the effect of Si addition on high-T_c YBCO are investigated for both bulk and thin film forms to clarify their electrical properties towards possible superconductor-semiconductor applications.

2. Experimental procedures

2.1. Bulk samples preparation

The starting materials were $Ba(NO_3)$, CuO, Y_2O_3 and Si powders with a purity 99.99%. The nominal composition has a formula $Y_1Ba_2Cu_3Si_xO_{7-\delta}$ with x ranging from 0.0 to 0.1. The mixture of each sample was ground and pressed into bars and heated to 920°C for 50 hr (for complete solid state interaction), cooled from 920°C to 680°C with cooling rate of 1°C/min and kept for 12 hr with flowing oxygen (to get the phase of superconductivity). Finally cooled from 680°C to 400°C (with rate 1°C/min) and kept for 12 hr(to get the optimum oxygen tontent value in the prepared samples), then left to cool to room temperature.

2.2. Thin film preparation

The YBCO thin film used in this study is deposited by laser ablation method on $SrTiO_3$ substrate. The substrate temperature operating at 750°C and the film thickness is 300 nm. The amorphous Si film of 600 nm thick is deposited directly upon YBCO thin film by radio frequency rf-glow discharge method of silane (SiH_4) at substrate temperature of 230°C.

2.3. DC measurement

Direct Current (DC) electrical resistance measurements are carried out by using the standard four probe method with silver contacts. The temperature was recorded by platinum electrode of 100 Ohm resistanca (Pt-100) thermometer.

The characterization of the thin films of YBCO and a-Si/YBCO are carried out by the induced voltage signal for T_c determination.

3. Results and discussion

The DC results of normalized resistance R/R_o (R_o: room temperature resistance) as a function of temperature of $Y_1Ba_2Cu_3Si_xO_{7-\delta}$ composite system is shown in fig. 1.

The normal part of resistance for pure YBCO and Si concentrations with $0 \le x \le 0.06$ have metallic behavior but those with $0.06 \le x \le 0.10$ are transformed into semiconductor like behavior.

The transition temperature to superconductivity T_c (R=0) is slightly decreased with Si doping of ($0 \le x \le 0.06$) then sharply decreased with Si doping of ($0.06 \le x \le 0.10$), table 1. The width of phase transition [$\Delta T_c = T_c(\text{onset}) - T_c(R=0)$] exhibited gradual increase with more Si doping in YBCO, table 1. The critical current density $\left(J_c = \dfrac{I_c}{area}\right)$ Am^{-2} is evaluated at room temperature and are listed in table 1. The decrease in both T_c and J_c by Si concentration and the increase in ΔT_c can be explained by the localization of free charge carriers by the dielectric phase of barium silicate due to the addition of Si into Y-Ba-Cu-O superconductor. It is also noted that the normalized resistance(R/R_o) is increased by increasing Si in YBCO, as shown fig. 1.

The room temperature resistivity ρ(290K), the resistivity at 100K i.e. ρ(100K) at temperature directly before T_c values and resistivity due to impurities and defects ρ(defect and impurities) (which is the independent part of resistivity on temperature) as a function of *Si* content are shown in fig. 2. From inspection of fig. 2, the pure YBCO has the following sequence of resistivities:

$$\rho.(290\text{K}) > \rho.(100\text{K}) > \rho.(\text{defect and impurities})$$

This is the normal sequence that indicating the metallic behavior of resistivity. By adding Si (x= 0.02), the three values of resistivities are all increasing and converged to each other, when x= 0.04, the three resistivities are strongly converging and are coincided at x= 0.06 due to the transformation to nearly insulating state. With more Si addition, at x= 0.08, the ρ(100K) is slightly greater than ρ(290K) indicating evidence the transition from metallic to semiconductor transport properties. Finally when x= 0.10, ρ(100K) is strongly greater than both ρ(290K) and ρ(defect and impurities) which supporting the transition from metallic to semiconducting behavior. The superconducting state is still present with slightly decrease of T_c by adding Si with low concentration (Si < 0.1 at %) in YBCO.

To investigate the superconducting properties of YBCO and *a*-Si/YBCO thin films, the transition temperatures T_c are recorded. The sharp T_c= 90 K for YBCO thin film, fig. 3-a and T_c for *a*-Si/YBCO *thin film has* two regions one at T_{c1}= 90K and the second at T_{c2}= 70K, fig. 3-b. This means that there is a second phase of superconductivity due to the deposited amorphous silicon (a-Si) on YBCO thin film.

According to semiconductor-superconductor composite model, YBCO composed of alternative superconductor and semiconductor layers [11]. The addition of Si into YBCO will increase the semiconductor layers and logically decrease the superconductor layers, which at x= 0.06 manifested in a changeover from metallic to semiconductor like behaviors. The doping of YBCO with Si produces dielectric barium silicate phases [12]. This starts to weaken the link between CuO_2-planes and Cu-O chains. The result is the reduction of the hole concentration in CuO_2-planes, this explains the decrease in both T_c, J_c and the increase in resistance due to Si addition into YBCO.

Difficulties in fabricating high quality YBCO thin films directly on Si arise from the main factor which is the intermixing and chemical interaction at the YBCO/Si interface. The lowest temperature at which high quality YBCO thin film can be deposited in situ on Si are around 600-800 °C. The alternative method to overcome this difficulty is to deposit a-Si thin film directly on YBCO because the deposition temperature is T_s= 230°C, this low temperature will slowdown the interdiffusion and chemical interaction between YBCO and a-Si thin films.

The combination between YBCO and Si thin films is a promising method for the development of superconductor- semiconductor devices.

4. Conclusions

1. The transition temperature to superconductivity T_c is reduced by Si addition to bulk YBCO with low Si concentration (Si ≤ 0.1 at %).
2. The a-Si/YBCO thin film has T_c in two steps; T_{c1}= 90K and T_{c2}= 70K due to the deposition of semiconductor onto superconductor and the formation of a second phase of barium silicate along side with the original superconducting phase.

Table 1
The critical temperature (T_c), its width (ΔT_c) and current density (J_c) as a function of Si concentration (x) in $Y_1Ba_2Cu_3Si_xO_{7-\delta}$

Si content (x)	T_c (K)	ΔT_c(K)	J_c(Am^{-2})
0.0	92	3	4.78×10^3
0.02	90	4	1.73×10^3
80	88	7	1.01×10^3
0.06	87	10	2.96×10^2
0.08	80	15	6.3×10^1
0.10	50	44	6.0×10^0

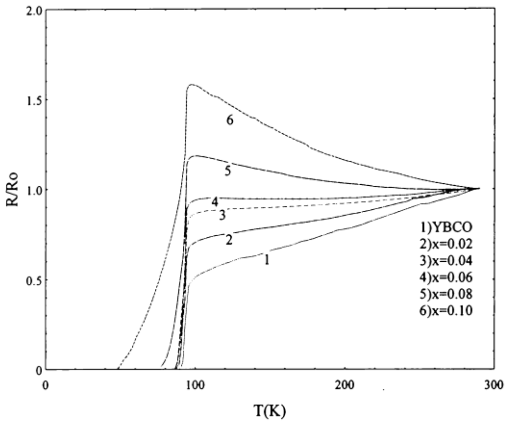


Fig. 1. Experimental results of the normalized resistance (R/R_o) as a function of temperature T(K) for $Y_1Ba_2Cu_3Si_xO_{7-\delta}$ compound.

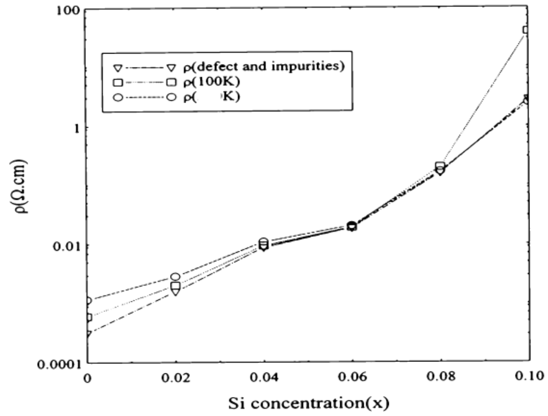
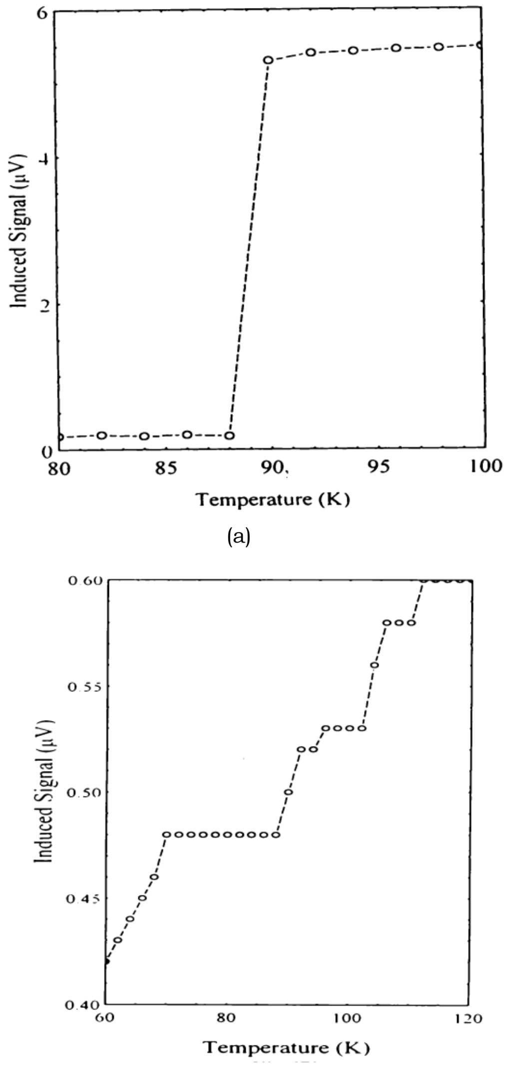


Fig. 2. The temperature resistivity ρ (290K), the resistivity at 100 K, ρ(100K) and the resistivity due to impurities and defects ρ (defects impurities) versus Si concentration (x) in YBCO.

3. The increase in transition width (ΔT_c) and the decrease in current density (J_c) with *Si* addition in YBCO is attributed to the localization of free charge carriers and the weakness of the link between CuO_2-planes and CuO-chains as a result of the second formed phase of barium silicate.
4. The conduction mechanism is transformed from metallic to semiconductor like behavior due to the coexistence of Si and YBCO in composite compound system.
5. Growth of amorphous silicon a-Si on high-T_c superconductors is of interest not only for future hybride devices, but also because a-Si is available as cheap and large-sized product.



(a)

(b)

Fig. 3. The induced signal as a function of temperature for determination the transition temperature *Tc* of: (a) YBCO thin film (b) Amorphous Si/YBCO films.

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