Electrical Properties and AC Susceptibility of CdTe Added Tl$_2$Ba$_2$CaCu$_2$O$_{8-δ}$ Superconductor

(Sifat Elektrik dan Kerentanan AU Superkonduktor Tl$_2$Ba$_2$CaCu$_2$O$_{8-δ}$ Ditambah dengan CdTe)

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ABSTRACT

Information on semiconductor/superconductor interface is important in fabricating devices of such hybrid systems. In this paper the electrical properties and AC susceptibility of Tl$_2$Ba$_2$CaCu$_2$O$_{8-δ}$ (TI-2212) superconductor added with CdTe semiconductor are reported. Samples with nominal starting composition Tl$_2$Ba$_2$CaCu$_2$O$_{8-δ}$ (CdTe), with $x = 0$ to 0.20 weight percent (wt. %) have been prepared by the solid-state reaction method. X-ray diffraction patterns showed essentially the TI-2212 phase with presence of impurities (CuO and Tl$_2$Ba$_2$CuO$_4$) for $x ≥ 0.05$ wt. % but did not change the TI-2212 structure which is tetragonal with lattice parameter $a = b ≠ c$. The critical onset temperature, $T_{c\text{-onset}}$, for all samples was between 104 and 108 K while the critical zero resistance temperature, $T_{c\text{-zero}}$, was from 93 to 95 K. The superconducting transition determined by AC susceptibility measurement showed $T_p$, between 101 and 103 K. The peak temperature, $T_p$, of the imaginary part of the susceptibility $χ''$ decreased for $x = 0.05$ and then increased for $x > 0.05$. This indicated that the superconducting grains were strongly coupled for $x > 0.05$ as a result of CdTe addition. The intergrain critical current density, $J_p$, at $T_p$ for the $x = 0.2$ sample $J_p (T_p = 95 K) = 23 A cm^{-2}$ was the highest among all samples. This sample also showed the highest $T_p$ indicating CdTe improved the flux pinning of the TI-2212 phase. This result can be useful in the fabrication of semiconductor/superconductor (TI-2212) hybrid devices.

Keywords: Intergrain coupling; superconductor/semiconductor interface; Tl$_2$Ba$_2$CaCu$_2$O$_{8-δ}$

INTRODUCTION

The TI-based cuprate superconductors have been of interest due to the relatively high transition temperatures. The effects of various elements and compounds on Tl$_2$Ba$_2$CaCu$_2$O$_{8-δ}$ (TI-2212) and other cuprate high temperature superconductors (HTSC) have been studied in order to improve the superconducting properties. This includes the effect of magnetic and non-magnetic particles, complex oxides, nanoparticles and various compounds on HTSC (Akimov et al. 2006; Annas et al. 2016; Awad et al. 2016; Gerashchenko et al. 1998; Hassan et al. 2016; Ji et al. 2013; Mumtaz et al. 2016). The optimal method to prepare the TI-2212 phase has also been reported (Abd-Shukor 1993).

The interface between semiconductor and superconductor is of interest from the fundamental as well as application point of view. Information on the transport properties at the interface can be useful in the fabrication of semiconductor/superconductor-based devices. The hetero-epitaxial growth of multilayer structures of HTSC and its integration with other technologies will help in the realization of advanced cryogenic-based devices.
An electron microscope was used to determine the transition temperature and intergrain critical current density of Tl-2212 thin films. The critical current density of Tl-2212 was found to exhibit a parabolic behavior with a maximum of 114 K around 7 GPa (Jian-Bo et al. 2015).

There has been some works on semiconductor/superconductor interface (Ji et al. 2013; Shirage et al. 2006). It was shown that HgCdTe/CdS hetero-structure have been reported (Cheung et al. 1991) and HgCdTe/YBa$_2$Cu$_3$O$_{7-x}$ from 30 K to 120 K was used to determine the susceptibility. The frequency of the AC signal was 295 Hz and the applied magnetic field was $H = 5$ Oe. The critical current density $J_c$ at the peak temperature $T_p$ of $\chi''$ was calculated using the Bean model (Bean 1964) with formula $J_c(T) = H(\mu_0)^2$ where $H$ is the applied magnetic field, $l$ and $w$ are the dimensions of the cross section of the bar-shaped sample. $T_p$ is the peak temperature of $\chi''$ of the AC susceptibility.

RESULTS AND DISCUSSION

The X-ray diffraction patterns of Tl$_2$Ba$_2$CaCu$_2$O$_y$(CdTe)$_x$ with $x = 0$, 0.05, 0.1, 0.15, 0.2 are shown in Figure 1. The diffraction peaks indicated that the $x = 0$ sample consisted of essentially the Tl-2212 phase with the tetragonal structure and space group 14/mmm and lattice parameter $a \neq b \neq c$. No significant changes in the lattice parameters of the Tl-2212 phase were observed as CdTe was added during the first and second heating stage, respectively (Cavdar et al. 2003). The superconducting transition temperature of Tl-2212 was found to exhibit a parabolic behavior with a maximum of 114 K around 7 GPa (Jian-Bo et al. 2015).

The samples were prepared by the solid-state reaction method. A precursor was prepared by mixing appropriate amounts of high purity (99.9+)% powders of BaO, CaO and CuO in an agate mortar to obtain a homogeneous mixture. The powders were heated for 48 h at 900°C with several intermittent grindings and furnace cooled. Tl$_2$O$_3$ and CdTe were added to the precursor powders and then pressed into pellets with approximately 13 mm diameter and 2 mm thickness. Excess 10% Tl$_2$O$_3$ was added to compensate for thallium lost during the heating process. The pellets were heated at 890°C for 4 min in oxygen flow followed by furnace cooling to room temperature.

The samples were analyzed by X-ray powder diffraction method using Bruker D8 Advance diffractometer with CuK$_\alpha$ source. The DC electrical resistance versus temperature measurements were carried out using four-point probe method with silver paste contacts in conjunction with a closed cycle refrigerator from CTI Cryogenics Model 22 and a temperature controller from Lake Shore Model 330. A constant current source between 1 and 100 mA was used throughout the measurements. Field Emission Scanning Electron Microscope (FESEM) micrographs were recorded using a Zeiss Supra 55 VP scanning electron microscope. An AC susceptibility from Cryo Industry model number REF-1808-ACS was used to determine the susceptibility from 50 K to 120 K. The samples were cut into bar shape for the AC susceptibility measurements. The frequency of the AC signal was 295 Hz and the applied magnetic field was $H = 5$ Oe. The critical current density $J_c$ at the peak temperature $T_p$ of $\chi''$ was calculated using the Bean model (Bean 1964) with formula $J_c(T) = H(\mu_0)^2$ where $H$ is the applied magnetic field, $l$ and $w$ are the dimensions of the cross section of the bar-shaped sample. $T_p$ is the peak temperature of $\chi''$ of the AC susceptibility.

FIGURE 1. X-ray powder diffraction patterns for Tl$_2$Ba$_2$CaCu$_2$O$_y$(CdTe)$_x$. (a) $x = 0$, 0.05 and 0.10 and (b) $x = 0.15$ and 0.20. (#) and (*) indicate CuO and Tl$_2$Ba$_2$CuO$_y$, respectively.
was added. With CdTe addition, minor impurities i.e. CuO and Tl$_2$Ba$_2$CuO$_6$ (Tl-2201) peaks were observed. No peaks from CdTe, Cd and Te compounds were observed indicating both Cd and Te may have been incorporated into the Tl-2212 phase. Previous works on CdO and CdTe addition in YBa$_2$Cu$_3$O$_7$ showed that these compounds exist separately and did not enter the YBa$_2$Cu$_3$O$_7$ crystal structure (Iguchi et al. 1988; Nur-Akasyah et al. 2017).

Figure 2(a) and 2(b) shows the FESEM micrographs for $x = 0$ and 0.10 samples, respectively. The $x = 0$ micrograph showed well defined grain boundaries. The addition of CdTe resulted in a smaller irregular grain size of less than 1 μm (Figure 2(b)). Figure 3 shows the EDX spectrum and weight percentage of each element for $x = 0.10$ wt. % sample. The spectrum showed a homogeneous distribution of Ce and Te in the Tl-2212 matrix.

The electrical resistance versus temperature curves are shown in Figure 4. The onset transition temperature, $T_{c-onset}$, is defined as the temperature where there is a sudden drop in resistance and can be obtained from the crossing point of the linear fit of the highest slope and the metallic high temperature part of the $\rho(T)$ curve for each sample. The zero-resistance temperature, $T_{c-zero}$, is the temperature where the resistance drops to zero and can be estimated from the extrapolation of the linear part of the resistance to the temperature axis. $T_{c-zero}$ for all samples
was between 104 and 108 K. The highest $T_{c\text{-onset}}$ was 108 K for the non-added TI-2212. $T_{c\text{-onset}}$ was between 93 and 95 K. The normal state resistance versus temperature curves showed metallic normal state behaviour for all samples. This is despite the significant change in the grain boundaries as a result of CdTe addition. The electrical resistivity at room temperature, $\rho_{297\text{K}}$ for the non-added sample was around 2.11 m\(\Omega\)cm. When CdTe was added, the resistivity increased to 13.52 m\(\Omega\)cm for the $x = 0.20$ wt. \% sample. The increase in the resistivity could be due to the changes in the grain size, which became smaller as CdTe was added. The room temperature resistivity $\rho_{297\text{K}}$, $T_{c\text{-onset}}$ and $T_{c\text{-zero}}$ are shown in Table 1.

The transition temperature as measured by AC susceptibility, $T_{c\gamma}$ for all samples was around 101 K and 103 K (Figure 5). The sudden decrease in the real part $\chi'$ of the complex susceptibility ($\chi = \chi' + i\chi''$) below the transition temperature indicates diamagnetic shielding and the peak in the imaginary part of the susceptibility, $\chi''$ represents the AC losses. $T_{c\gamma}$ does not change very much with CdTe addition. $T_{c\gamma}$, $T_p$ and $J_c(T_p)$ are shown in Table 1. The peak temperature, $T_p$ of the imaginary part of the susceptibility $\chi''$ increased as CdTe was added except for $x = 0.05$ wt. \% where $T_p$ decreased. Upon increase in CdTe content, $T_p$ shifted to higher temperatures due to the strengthening of the pinning forces. At $T_p$, the AC field amplitude is equal to the full flux penetration field. The intergrain critical current density, $J_c$ at $T_p$ for the samples are shown in Table 1. The $x = 0$ sample showed $J_c(T_p = 90\text{K}) = 20\text{ A cm}^2$ and for $x = 0.2$, $J_c(T_p = 95\text{K}) = 23\text{ A cm}^2$. The increase of $T_p$ from 90 K to 95 K and increase in $J_c(T_p)$ showed that CdTe improved the flux pinning capability of the TI-2212 phase. No CdTe peaks were observed in the XRD pattern. Hence, the increase in the critical current density may be due to the changes in the microstructure as CdTe was added which enhanced the inter-grain coupling.

In conclusion, samples with nominal starting compositions $\text{Tl}_2\text{Ba}_x\text{CaCu}_8\text{O}_{y}\text{(CdTe)}$, with $x = 0, 0.05, 0.1, 0.15, 0.2$ have been prepared. CdTe addition showed the presence of CuO and TI-2201 impurity phase but very small change in the transition temperature. Cd and Te were homogeneously distributed in the samples. The grain size of the samples decreased as CdTe was added. The coupling between grains was strengthened resulting in increase of $T_p$ for $x > 0.05$ wt. \%. These results are useful in the fabrication of semiconductor/superconductor hybrid devices.

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<th>$a$ / Å</th>
<th>$c$ / Å</th>
<th>$T_{c\text{-onset}}$ / K</th>
<th>$T_{c\text{-zero}}$ / K</th>
<th>$T_{c\gamma}$ / K</th>
<th>$T_p$ / K</th>
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**TABLE 1.** $\rho_{297\text{K}}$, lattice parameter $a$, and $c$, $T_{c\text{-onset}}$, $T_{c\text{-zero}}$, $T_{c\gamma}$ and $J_c(T_p)$ of $\text{Tl}_2\text{Ba}_x\text{CaCu}_8\text{O}_{y}\text{(CdTe)}$ for $x = 0, 0.05, 0.10, 0.15$ and $0.20$.

**FIGURE 5.** AC susceptibility ($\chi = \chi' + i\chi''$) versus temperature of $\text{Tl}_2\text{Ba}_x\text{CaCu}_8\text{O}_{y}\text{(CdTe)}$, for $x = 0, 0.05, 0.10, 0.15$ and $0.20$. 

This figure shows the AC susceptibility ($\chi = \chi' + i\chi''$) versus temperature for different compositions of $\text{Tl}_2\text{Ba}_x\text{CaCu}_8\text{O}_{y}\text{(CdTe)}$, with $x = 0, 0.05, 0.10, 0.15$ and $0.20$. The susceptibility ($\chi''$) peaks at different temperatures ($T_p$) which are shown in Table 1.
REFERENCES


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