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Time Dependence of the Resistivity of the Fe-Sb System at Room Temperature

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Abstract In this paper, the synthesis, resistivity measurement, and X-ray diffraction of the Fe-Sb system are reported. The method of synthesis of the Fe-Sb system, which instigates the formation of the $FeSb_2$ and FeSb phases between Fe grains at the interface, was found to cause a decrease in resistivity. The sample produced an anomalous result for resistivity behavior at room temperature, where a time-dependent change in the electrical resistivity was observed. This change can be expressed by the exponential function of time.

Keywords: *four-point probe, resistivity, binary compounds*

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1. Introduction

It has been shown that when the electrical resistivity of a material abruptly drops and gradually decreases to zero, these behaviors are temperature dependent [1,2] and time dependent [3,4], respectively. These resistivity behaviors, which occur in certain conditions for physical states, reveal important information about the scattering mechanisms of electrons. The temperature dependence of lattice resistivity has been shown to be dominated by electron-phonon scattering [5], whereas the time dependence of residual resistivity has been observed in structural scatterings [5] at room temperature [3].

Antimony (Sb) with iron (Fe) plays an important role in material science. For instance, in quaternary oxypnictide compounds with Sb in the conduction layer FePn (Pn=pnictogen), a semiconductor-superconductor phase transition has been observed only with an element Sb in the $LaO_{0.89}F_{0.11}FeSb$ compound [6], where this compound showed an anomalous change in the resistivity curve. Also, the partial replacement of As with Sb causes enhancement of the superconducting transition temperature in the $LaO_{0.8}F_{0.2}FeAs_{1-x}Sb_x$ compound [1]. On the other hand, in binary compound $FeSe_{1-x}Sb_x$ [7], the partial substitution of Se with Sb causes an anomalous change in the resistivity curve which has been ascribed to a structural transition. However, many researches have focused on investigating the electronic and magnetic properties of iron with non-transition elements with fully occupied d-levels such as Sb, Ge. As regards the temperature dependence of the resistivity measurement, the presence of Ge in the conduction layer in the $LaO_{1-x}F_xFeGe$ compound has been found to result in a large decrease in T_{anom} from 150 K for LnOFeAs (Ln= La, Sm, Ce, Gd) to 90 K for LaOFeGe [2]. In the present paper, the synthesis, resistivity measurement, and X-ray diffraction of the Fe-Sb system are reported. The results reveal a time-dependent change in electrical resistivity with the exponential functions of time. This finding provides a new starting point for research on reducing the resistance of conduction electrons in an impure metal through the utilization of specific phases.

2. Experiment

The Fe-Sb sample was synthesized using a conventional solid state reaction technique by heating high-purity starting materials (Fe and Sb powders). The Sb powder was placed in a pressing boat and then the Fe powder was placed on top of the Sb powder without mixing (i.e. layer upon layer) and then pressed into a pellet. The pellet was placed between two boats of tungsten inside a chamber evacuated at 10^{-5} Torr. The pellet was heated at high current by electrical poles at both ends of the boats at 160 A for 2 hour and then 200 A for 2 hour. The final pellet was sealed in an evacuated silica tube and then annealed in a furnace at 600°C for 12 h. The product, a circular pellet, which had a thickness 1.7 mm and a diameter 13 mm, consisted of two thick layers of Fe on Sb. The four-point probe technique at room temperature was used to measure DC resistivity of the sample on the Fe surface at a constant current of 1.6 mA, where the sample was contacted to four copper wires with silver conducting paint. To remove residual moisture, the sample was placed in a vacuum that was backfilled with helium and then held at a pressure of 760 Torr and a temperature of 293 K.

3. Results and Discussion

Figure 1 shows the X-ray diffraction pattern for the Fe-Sb sample. The many peaks were determined to be Fe and Sb elements. In addition, the presence of some $FeSb_2$ and FeSb phases was detected. Figure 2 shows the resistivity as a function of time for the Fe-Sb system. It can be seen that the voltage value across the two inside probes decreases gradually with the passage of time. The measured resistance as a function of time (plotted as dotted lines) can be expressed by the exponential function of time $\rho=A\exp(-\alpha t)+B$, which was proposed in [3]. The corresponding parameter values are A=4.43897 Ωcm, α=0.02136 min^{-1}, and B=1.45282 Ωcm. A good fit was obtained by applying a different fitting function $\rho=A_1\exp(-\alpha_1 t)+A_2\exp(-\alpha_2 t)-B_0$, which was proposed in [4], with fitting parameters A_1=2.9511 Ωcm, α_1=0.03842 min^{-1}, A_2=3.2347 Ωcm, α_2=0.00427 min^{-1}, and B_0=0.08777 Ωcm. The transport properties are dominated by the scattering mechanisms in the sample. Therefore, the decreasing in the resistivity shown in Figure 2 indicates low structural scatterings and phonon scattering, and this leads to enhanced carrier density. This unexpected anomalous result for resistivity behavior was observed at room temperature and at 77-300 K in the Ohmic switches with conducting contacts, and can be described by a power law relation that is derived from the single asperity model, thus demonstrating that the coefficient of the power law is directly related to the creep coefficient and that the prefactor to the power law is related to the initial roughness of the contact [3]. A time-dependent change in the electrical resistivity was also observed in polycrystalline YSZ (Y_2O_3 - stabilized ZrO_2) and CSZ (CaO-stabilized ZrO_2) samples at 1100°-1350℃ in air, which can be explained by the equilibrium of the association reaction of oxide ion vacancies, VO, and doped cations, Y_{Zr} or Ca_{zr} [4]. The change in resistivity in these samples, which can be expressed by the exponential functions of time, consists of bulk resistance and grain boundary resistance, where bulk resistance changes more rapidly compared with grain boundary resistance. However, this behavior was also observed in a Pt/Co/AlOx/Pt system under sustained voltage application, which suggests that there is electromigration of charged oxygen vacancies near the Co/AlOx interface that are driven by the effective electric field within the dielectric [8].

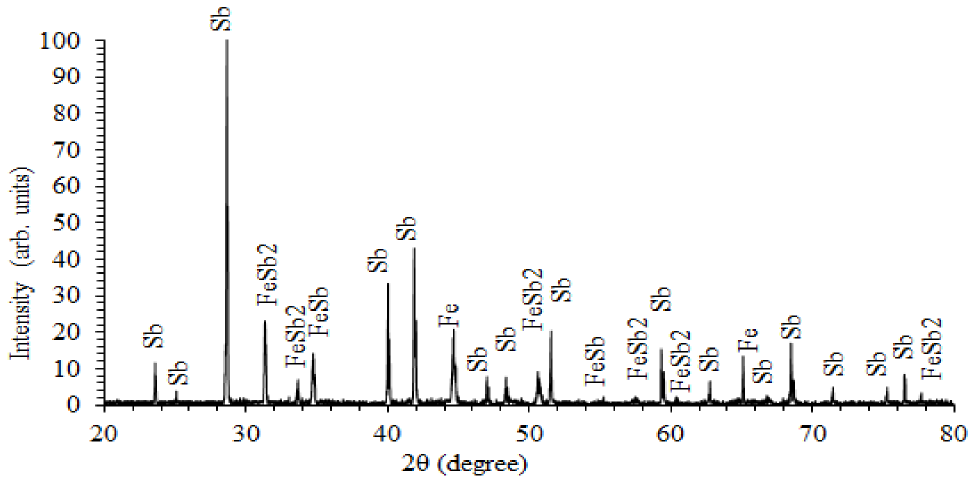

Figure 1. XRD measurement of the Fe-Sb sample directly after synthesis. All the diffraction peaks are marked by the Fe, Sb, FeSb, FeSb2 phases

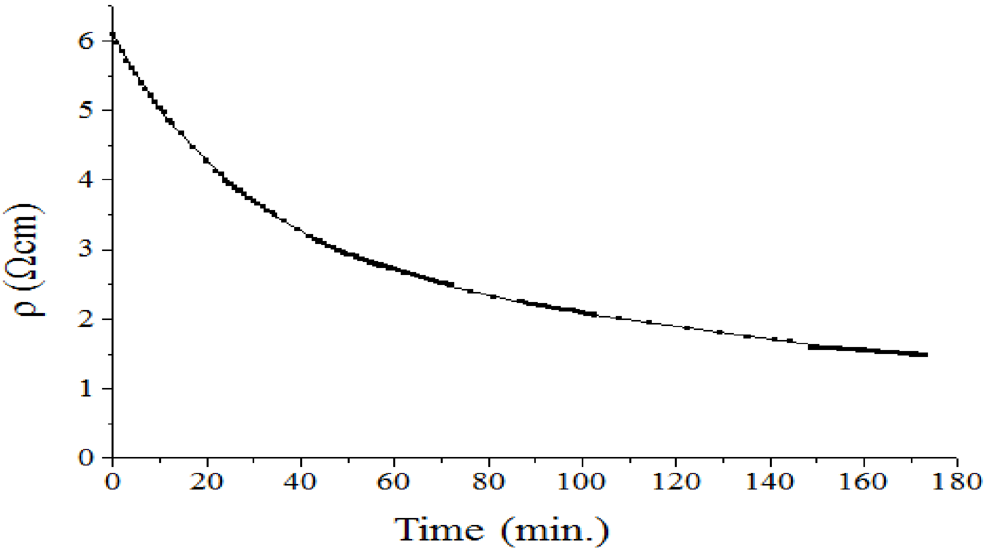

Figure 2. Time dependence of the resistivity of the Fe-Sb system. The solid line is a fit of equation $\rho=A_1\exp(-\alpha_1 t)+A_2\exp(-\alpha_2 t)-B_0$

Total resistivity is the sum of residual resistivity ρ_0 due to structural scatterings (such as grain boundary scattering, impurity scattering and surface scattering) and lattice resistivity ρ_{ph} due to scattering by phonons [5]. Structural scatterings are basically independent of temperature, whereas scattering by phonons is temperature dependent [5], although there is a temperature-independent electron-phonon interaction contribution in the $FeSb_2$ phase [9]. At the interface of the Fe-Sb system, the current of the conduction electrons flows through the ferromagnetic conducting Fe grains that are in contact with the nonmagnetic semiconducting $FeSb_2$ phase [10,11,12] and FeSb phase. The $FeSb_2$ has a strong electron-phonon interaction [9], and FeSb phase that showed an almost temperature-independent form of resistivity [13]. Electron-phonon interaction can cause a change in resistivity, where the scattering between electrons and phonons is drastically reduced with an increasing concentration of $FeSb_2$ and FeSb phases between Fe grains. It has been found that the $FeSb_2$ phase has giant carrier mobility and a small energy gap [10,11,14]. The time dependence of the resistivity under electric current within the Fe surface could be explained by the electromigration of charged vacancies near the Fe-Sb interface of the Fe grains and the $FeSb_2$ and FeSb phases. In general, no direct evidence or rule has been presented for predicting the time-dependent resistivity at room temperature. However, certain other factors may also cause changes in the interactions among electrons (i.e., electron scattering and electron-phonon scattering).

4. Summary

The time-dependent change in the electrical resistivity of the Fe-Sb system was investigated by applying a four-point probe to the Fe surface at room temperature. It was determined that the change in resistivity can be expressed by the exponential functions of time. An approach that utilizes the formation of $FeSb_2$ and FeSb phases between the Fe grains at the Fe-Sb interface as a means to improve the time dependence of resistivity would seem to be a very effective way to reduce the voltage value across the two inside probes. Such an approach could be a promising strategy to improve the transition temperature of resistivity for superconducting materials.

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