Superconductivity in an Aluminum Film Grown by Molecular Beam Epitaxy

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We report on superconductivity in an aluminum film grown on a GaAs substrate by molecular beam epitaxy (MBE). We show that the quality of the MBE-grown sample is better than that of its counterpart prepared by electron gun evaporation. This is evidenced by the observed much lower resistivity, higher critical current, longer coherence length, and downward critical field-temperature characteristic $H_c(T)$. Our results suggest that a MBE-grown Al thin film can be used to study superconductivity in a relatively clean metal.

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Being the most widely used non-ferrous metal, aluminum has been found to have wide applications in heat sinks for electronic appliances such as transistors, CPUs, electrical transmission lines for power distribution, and so on. As a result, it is highly desirable to prepare high-quality aluminum materials for practical applications. In particular, the epitaxial growth of Al films on GaAs substrates has attracted much interest because of its relevance to the field of electronic interconnects [1–6]. Recently it has been suggested that negative differential conductance can be achieved in tunnel Schottky structures by utilizing an *in-situ* Al film grown by molecular beam epitaxy (MBE) [6].

It is well known that below a characteristic temperature, T_c, some metals such as aluminum lose their electrical resistance abruptly, becoming superconductors. Such an effect can be well described by the formation of many-body electron pairs, so called Cooper pairs [7, 8]. It is well established that a superconductor like aluminum can sustain a dissipationless current (supercurrent). Switching from superconducting to dissipative conduction can occur when the current I through a superconductor approaches a critical value, I_c, resulting in a sudden appearance of a finite resistance. Similarly, the application of a magnetic field up to a critical value, H_c, can completely destroy the zero-resistance state.

Although preparation and characterization of MBE-grown Al films have been studied in depth, studies of the superconducting behavior of Al thin films grown by MBE are still lacking. Such experimental works may shed light on superconductivity in less-disordered metals compared with that in the counterparts prepared by other methods, such as electron beam evaporation and sputtering. Moreover, it may allow us to compare experimental results of superconductivity in less disordered metals with related theory and models. In this paper, we present superconductivity in an aluminum film grown by MBE. For comparison, we present measurements on a control sample with the same thickness prepared by electron

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gun (e gun) evaporation. We show that the quality of the MBE-grown sample is better than that of the film prepared by e gun evaporation. This is supported by the observed lower resistivity and the much lower critical magnetic field—and hence much longer coherence length—in our MBE-grown Al film. Moreover, the critical current for which our MBE-grown Al film can sustain a dissipationless current is three times higher than that for its counterpart prepared by e gun evaporation. These results indicate an advantage for using MBE-grown components, such as Al thin films.

Both aluminum films of the same thickness of 60 nm were grown on GaAs (001) substrates. The details of our sample preparation will be described elsewhere. For clarity, we denote the film grown by MBE as sample A and the aluminum film prepared by electron gun evaporation as sample B. At room temperature (RT), the resistivity ρ of sample A is measured to be 2.99×10^{-8} Ω m. In contrast, the ρ of sample B is determined to be 1.65×10^{-7} Ω m, almost an order of magnitude higher than that of sample A. We note that the ratio $\rho_{\rm RT}/\rho_{\rm 4K}$ may be regarded as a measure of sample quality, since at low temperatures residue impurity scattering dominates [9]. At higher temperatures electron-phonon scattering increases, thereby increasing the resistance of a metallic system. The ratio $\rho_{\rm RT}/\rho_{\rm 4K}$ is therefore related to residue imperfection scattering and electron-phonon scattering within a metal. In our case, $\rho_{\rm RT}/\rho_{\rm 4K} \sim 20.3$ and ~ 1.84 for sample A and sample B, respectively. These results demonstrate that the purity and quality of sample A are better than those of sample B. Experiments were performed in a top-loading He^3 cryostat. Four-terminal resistivity measurements were performed using standard ac phase-sensitive lock-in techniques. Current-voltage characteristics of the devices were measured in the dc mode. The magnetic field is applied perpendicular to the plane of the Al films.

Figure 1 (a) shows resistivity measurements on sample A as a function of magnetic field H at various temperatures. At the lowest measurement temperature of 0.276 K, we observe vanishing resistivity ρ near $H = 0$. For a given T, once the applied magnetic field reaches a certainly value, ρ shows a dramatic increase and reaches its saturation value of 1.47×10^{-9} Ω m. This can be ascribed to suppressed superconductivity in an applied H. For comparison, the ρ_H of sample B at various T is shown in Fig. 1 (b). Similarly, ρ shows a dramatic increase and reaches its saturation value of 8.89×10^{-8} Ω m in the normal state once H reaches a certain value.

We are now in a position to compare the results shown in Fig. 1 (a) with those depicted in Fig. 1 (b). From the resistive mid points at various T, that is, when the resistance of sample A reaches half of the normal state at a certain H, we are able to determine $H_c(T)$. Such results are depicted in Fig. 2 (a). Similarly, the $H_c(T)$ of sample B were determined and plotted in Fig. 2 (b).

For sample A, $H_c(T)$ shows a downward behavior, consistent with that described by the BCS model. As shown in Fig. 2 (a), there is a good fit to the following equation:

$$H_c(T) = H_c(0)\left[1 - \left(\frac{T}{T_c}\right)^2\right], \tag{1}$$

where $H_c(0)$ is the critical field at $T = 0$ K, and T_c is the critical temperature. From the fit shown in Fig. 2 (a), we are able to determine $H_c(0)$ and T_c to be 43 Gauss and 1.153

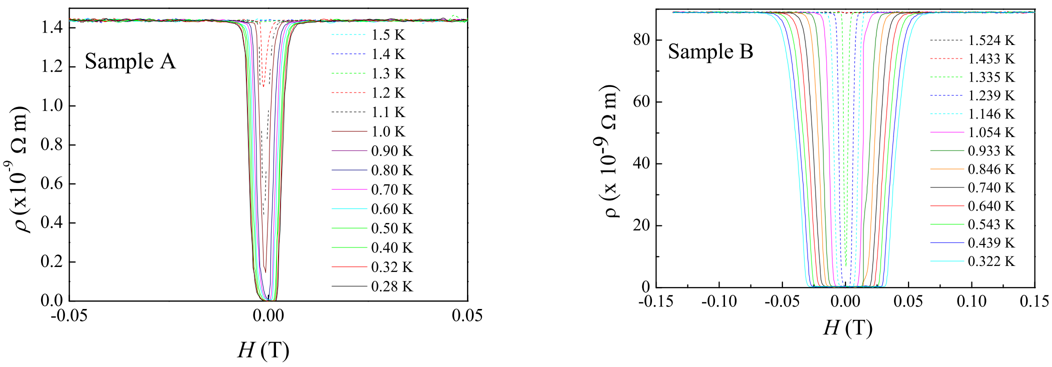

FIG. 1: Resistivity measurements as a function of the magnetic field ρ_H for (a) sample A and (b) sample B at various temperatures T.

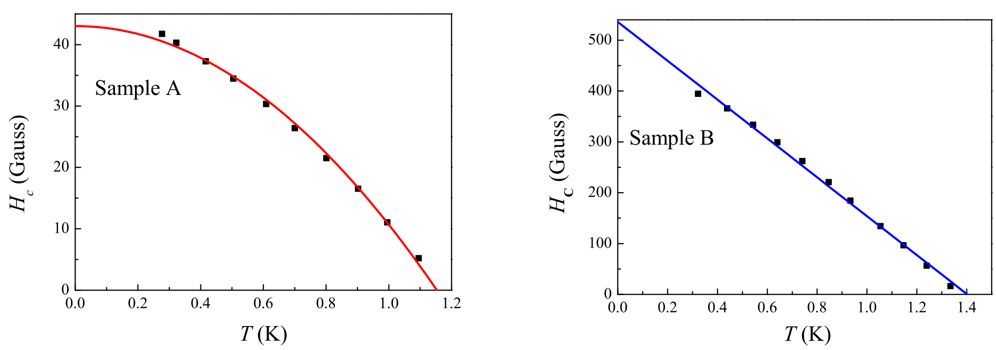

FIG. 2: Critical magnetic field at different temperatures $H_c(T)$ for (a) sample A and (b) sample B. A fit to Eq. (1) is shown in a red curve, and a fit to Eq. (2) is shown in a blue straight line.

K, respectively. The coherence length is estimated to be 8.86μm. In contrast, the $H_c(T)$ of sample B can no longer be described by Eq. (1). Instead, an empirical equation,

$$H_c(T) = H_c(0)\left[1 - \left(\frac{T}{T_c}\right)\right], \tag{2}$$

can be used to fit the measured $H_c - T$ data. For sample B, $H_c(0)$ and T_c are measured to be 536 Gauss and 1.4 K, respectively. The corresponding coherence length is estimated to be 78 nm. Maekawa, Ebisawa, and Fukuyama [10] pointed out that in a dirty superconductor, H_c can be enhanced at low T and even shows upward curvature. Indeed, experimentally Shinozaki, Kawaguti, and Fujimori have shown that in a dirty superconductor, instead of seeing a downward curve $H_c(T)$, one sees a linear or even an upward curve of $H_c(T)$ [11]. The observed linear $H_c(T)$ in sample B again demonstrates that sample B is of poorer quality compared with sample A. Although quality-wise sample A is better than sample B, we note that the measured T_c of sample A ($T_c \sim 1.15$ K) is substantially lower than that of sample B ($T_c \sim 1.4$ K). It is known that some granular superconductors can have transition temperatures appreciably higher than the ordinary value [12]. Moreover, AFM studies of both films suggest that the surface roughness of sample B is much higher than that of sample A. Therefore it is possible that sample B is granular-like; thus its T_c is higher than that of sample A.

As mentioned earlier, a superconductor can sustain a dissipationless current. This effect may be used to reduce heat dissipation in integrated circuits. It is thus interesting to compare the threshold for dissipationless current our Al films can sustain. Figure 3 (a) shows the four-terminal $I-V$ characteristic of sample A. At a low current, a vanishing voltage is detected, demonstrating that our film is in the superconducting state with zero resistance. Once the applied current reaches a threshold of 4.4 mA, a switching from superconducting to dissipative conduction is observed. Similar results are obtained on sample B, as shown in Fig. 3 (b). We can clearly see that the threshold current for sample A is about three times higher than that for sample B (~ 1.34 mA). This result suggests that a MBE-grown Al film is a better superconducting component compared with its counterpart prepared by electron gun evaporation.

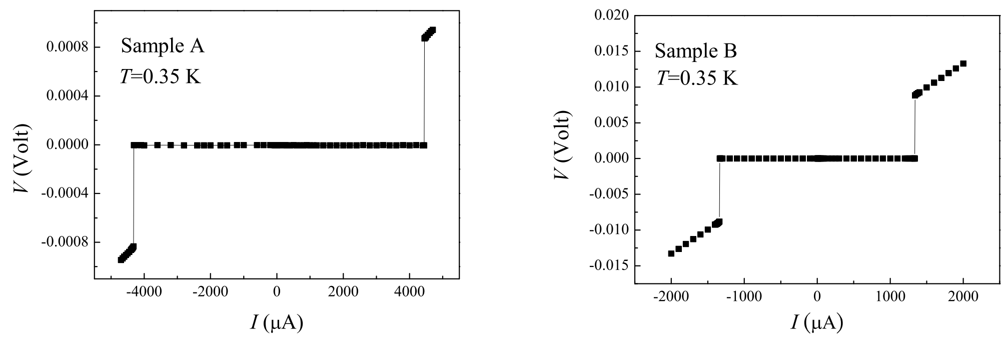

FIG. 3: Four-terminal current-voltage ($I-V$) characteristics of (a) sample A and (b) sample B. Critical currents are determined by the abrupt switching from superconducting and dissipative conduction.

In conclusion, we have demonstrated that a high-quality aluminum thin film grown by MBE is of higher quality compared with its counterpart prepared by electron gun evaporation. This is evidenced by the much lower (~ 1 order) resistivity at room temperature and a much higher ratio (~ 12 times) of the resistivity at RT to that at liquid helium temperatures $\rho_{\mathrm{RT}}/\rho_{4\mathrm{K}}$. Moreover, superconductivity in MBE-grown Al film was studied. It was found that the critical magnetic field as a function of T can be better described by the BCS-type theory. Our results suggest that a MBE-grown Al thin film is an ideal playground for studying superconductivity in a less-disordered metal compared with its counterparts prepared by other methods, such as electron gun evaporation and sputtering.

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