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Effect of electrically degenerated layer on the carrier transport property of ZnO epitaxial thin films

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ABSTRACT

ZnO films were prepared on (1 1 1) YSZ and (0 0 0 1) sapphire by pulsed laser deposition method. Effect of lattice mismatch on the carrier transport properties of ZnO epitaxial thin films was investigated. The carrier mobility of the ZnO films on YSZ was larger than that of ZnO/sapphire due to smaller lattice mismatch when the thickness was below 150 nm. The effect of electrically degenerated layer on the carrier transport property increased with decreasing the film thickness of ZnO film. The carrier density and electron mobility of 20 nm-thick-ZnO film on either substrate were regardless of the temperature. We concluded that the dominant carrier scattering mechanism in ZnO ultra thin films is double Schottky barriers at the grain boundary and that their height depends on the carrier concentration.

1. Introduction

ZnO, which is II–VI compound semiconductor, has a wide band gap of 3.37 eV and a large exciton binding energy of 60 meV at room temperature. Therefore, it has been expected to application for optical devices such as light-emitting diode and laser diodes [1].

For the film deposition of ZnO, sapphire substrate is mostly used because it has advantages of hexagonal crystal symmetry, low cost and thermal stability. However, it has been reported that a degenerated layer is formed at the interface, when ZnO or GaN film is deposited on sapphire (0 0 0 1), which has a large lattice mismatch against each film [2,3].

In this study, we prepared ZnO epitaxial films on sapphire and Yttrium Stabilized Zirconia (YSZ) (1 1 1), whose lattice mismatches against ZnO were 18 and 10%, respectively. The effect of degenerated layer at the ZnO/YSZ or ZnO/sapphire interface on the electrical transport property is studied. The carrier density and the film thickness dependence are also examined.

2. Experiment

ZnO films were deposited by pulsed laser deposition (PLD) method. Growth conditions were 600 °C of substrate temperature and 1×10^{-5} torr of oxygen pressure. The thickness of the ZnO film was varied from 20 nm to 1 μm. The surface morphology of the films was analyzed by atomic force microscope (AFM). The structural analysis was carried out using X-ray diffraction (XRD) and the electrical transport property was measured by Hall effect using van der pauw configuration.

3. Results and discussion

Fig. 1(a) and (b) shows the temperature dependence of the electron mobility (a) and the carrier density (b) of ZnO epitaxial films on sapphire. Closed triangles, squares and circles correspond to those of 1, 150 and 20 nm-thick-ZnO films, respectively. As shown in Fig. 1(a), the mobility of 1 μm-thick-ZnO is 94.4 cm^2/V s at 300 K and it increases with decreasing the measurement temperature down to 100 K due to decreasing the phonon scattering like as normal semiconductor, then, it drastically decreases with decreasing temperature and reaches 1.3 cm^2/V s at 10 K because of increase the ionic scattering effect. The mobility of 150 nm-thick-ZnO film is 52.0 cm^2/V s at 300 K and it does not change from 300 to 200 K. No semiconducting transport behavior is observed in this temperature region. It decreases with decreasing the temperature and becomes 1.9 cm^2/V s below 50 K suggesting that there is an effect of electrically degenerated layer at ZnO/sapphire interface. The mobility of 20 nm-thick-ZnO film is 3.3 cm^2/V s at 300 K which is much smaller than that of 150 nm-thick-ZnO film due to the increasing the effect of degenerated layer. These results indicate that the effect of electrically degenerated layer increases by decreasing the film thickness.

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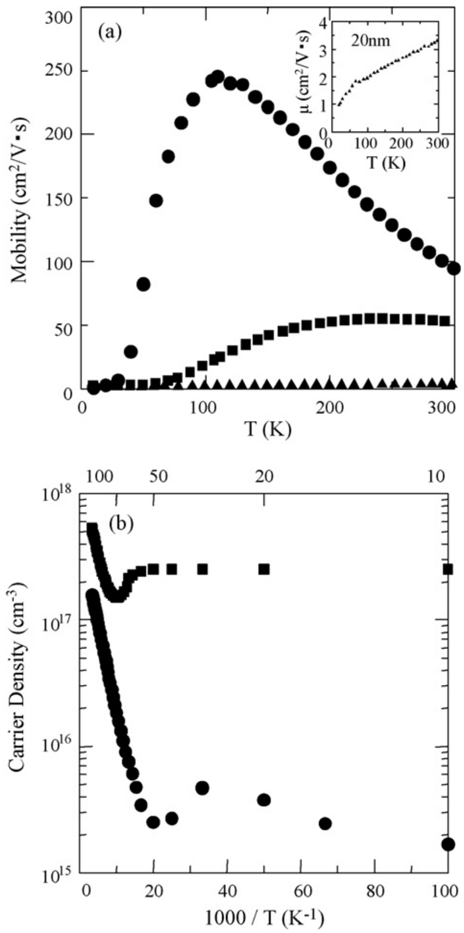

Fig. 1. Mobility (a) and carrier density (b) of 20 nm (▲), 150 nm (■) and 1 μm (●)-thick-ZnO films on (0 0 0 1) sapphire. The inset figure shows the mobility of 20 nm-thick-ZnO film.

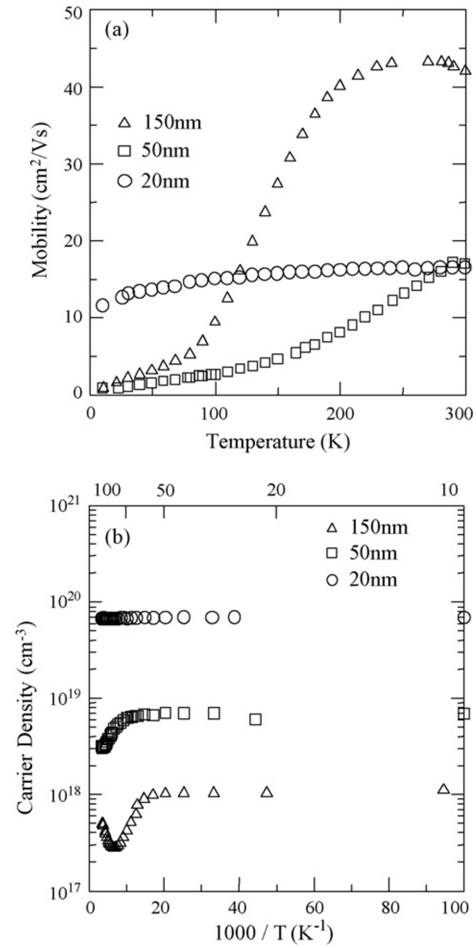

Fig. 2. Mobility (a) and carrier density (b) of 150, 50 and 20 nm-thick-ZnO films on (1 1 1) YSZ.

As shown in Fig. 1(b), the carrier density of 1 μm-thick-ZnO film exponentially decreases with decreasing temperature down to 50 K like as normal semiconductor. Then, it increases until 25 K and then gradually decreases with decreasing the temperature. Although that of 150 nm-thick-ZnO film also exponentially decreases with decreasing the temperature from 300 to 100 K, it does not change below 50 K like metallic material, supporting there is the effect of electrically degenerated layer below 50 K. The carrier density of 20 nm-thick-ZnO film which is not in Fig. 1(b) was 1.3×10^{20} cm^{-3} regardless of the temperature. These results also support that the effect of degenerated layer on the carrier density for 1 μm-thick-ZnO film is smaller than those of 150- and 20-nm-thick-ZnO. By analyzing these transport behaviors by two layered model [2] distinct evidence of existing the degenerated layer was recognized and the thickness of the degenerated layer for 1 μm and 150 nm-thick ZnO film were calculated to be 0.7 and 11.3 nm, respectively. For 20 nm-thick-ZnO, however, the experimental result were not able to be fit suggesting that only the degenerated layer was responsible for the carrier transport of the film.

Fig. 2(a) and (b) show the temperature dependence of the mobility (a) and the carrier density (b) of ZnO epitaxial films on (1 1 1) YSZ. Open triangles, squares and circles correspond to those of 150, 50 and 20 nm-thick-ZnO films, respectively. As shown in Fig. 2(a), the mobility of 150 nm-thick-ZnO film slightly increases from 300 to 200 K, then, it decreases to 1.0 cm^2/V s below 30 K. This behavior is quite similar to that of 150 nm-thick-ZnO film on sapphire indicating that the effect of lattice mismatch for the carrier transport properties is little for 150 nm-thick-ZnO film. The mobility of 50 nm-thick-ZnO film decreases with decreasing the temperature and becomes 1.5 cm^2/V s under 50 K. This result supports that there is an effect of electrically degenerated layer below 30 K. The mobility of 20 nm-thick-ZnO film is 16.5 cm^2/V s at 300 K which is much higher than that of ZnO film grown on (0 0 0 1) sapphire due to smaller lattice mismatch. Although the effect of lattice mismatch was not predominant when the film is thick, it became obvious for thinner film.

However, the temperature dependence was identical to that of ZnO/sapphire, namely no mobility drop at low temperature is observed. It is 11.6 cm^2/V s even at 10 K. This interesting transport phenomenon should be responsible for lowering the effect of double Schottky barrier probably originated from higher carrier density in the ZnO thinner film. This will be discussed later. As shown in Fig. 2(b), the carrier density of 150 nm-thick-ZnO decreases with decreasing the temperature from 300 to 150 K and it once increases with decreasing the temperature down to 50 K. Below 50 K, it shows fixed value due to the existence of the degenerated layer, which is metallic. The carrier density of 50 nm-thick-ZnO increases with decreasing temperature from 300 to 80 K and becomes constant value under 80 K indicating that the effect of the degenerated layer shifted to higher temperature side. From these results, the effect of the degenerated layer on the carrier transport becomes stronger by decreasing the film thickness. On the other hand, the carrier density of 20 nm-thick-ZnO film is regardless of the measurement temperature suggesting there is an effect of degenerated layer even at the room temperature.