High-Mobility TiO₂-Channel TFTs with Optimized Anatase Microstructures

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Abstract

Titanium dioxide (TiO_2) , the material which has been applied to a range of functional devices, was embedded as a channel material in a TFT. After optimizing fabrication process, especially the post-annealing temperature, the mobility of the TiO₂-channel TFT exceeded 8 cm²/Vs, an order of magnitude higher than most of the reported values. The detailed structural analysis revealed that the polycrystalline TiO₂ films have triple-grain structures, one inside another, with the length scale from 0.1 μ m to 10 μ m. The post-annealing grew both the grain and the boundary, especially those with 0.1 μ m length scale, leading to the highest mobility at the medium temperature.

1. Introduction

An oxide semiconductor TiO_2 is distinct from conventional semiconductors, showing various photo- and electro-chemical phenomena such as photocatalysis and resistance switching. Gate control of these distinctive phenomena can diversify the concept of electronics, as well as help understand the electronic mechanisms behind them.

Field effect mobility (μ_{FE}) characterizes the performance of thin film transistors (TFTs), defining the speed or the driving current of the whole device. Relatively localized nature of Ti 3*d* orbit is likely to cause small μ_{FE} in TiO₂-channel TFTs, ~1 cm²/Vs (room temperature) at most so far. On the other hand, Nb doping to single crystal anatase TiO₂ films can achieve the Hall mobility more than 8 cm²/Vs[1], clearly indicating that μ_{FE} in TiO₂-channel TFTs has yet to be improved.

In this study, the structural factor was pointed out which has limited μ_{FE} in TiO₂-channel TFTs, especially related to the triple-grain structures of the TiO₂ films in the length scale from 0.1 µm to 10 µm. By optimizing these structures, μ_{FE} beyond 8 cm²/Vs was demonstrated, an order of magnitude higher than most of the reported values. The essential message here is that by optimizing the grain size/crystallinity while minimizing the boundary effect, the electron mobility in the polycrystalline channel can reach comparable to that in the single crystalline film.



Fig. 1 (a) Mass density of TiO₂ films evaluated from X-ray reflectivity. (b) X-ray diffraction of post-annealed TiO₂ films for three different P_{O2} . "R" and "A" represent rutile and anatase.



Fig. 2 (a) Transfer characteristics of TiO₂-channel TFTs post-annealed at various $T_{\rm a}$. (b) $\mu_{\rm FE}$ plotted as a function of $T_{\rm a}$.

2. Experimental

40 nm TiO₂ films were deposited on SiO₂(115 nm)/n⁺[5 $\times 10^{18}$ /cm³]:Si(001) substrates by pulsed laser deposition. The substrate temperature was kept at room temperature, which may lead to the higher electron mobility in TiO₂ films according to the past literature[2]. The oxygen pressure (P_{O2}) during the deposition was controlled to make a single anatase phase. The deposited TiO₂ films were crystallized by 1 bar N₂ post-annealing for 1 hour at various temperatures (T_a). Al was thermally evaporated as the source and drain electrodes for the TiO₂ channel of 100 µm \times 400 µm.

3. Results

When P_{O2} during the deposition was varied from 0.1 Pa to 4 Pa, the mass density of the as-deposited films decreased from 4.4 g/cm³ (~ rutile phase), 3.9 g/cm³ (~ anatase phase), to 3.2 g/cm³ (much lighter than that of the anatase phase) (Fig. 1a). Accordingly, post-annealing at 500 °C resulted in crystallization of the rutile dominant phase for 0.1 Pa, the single anatase phase for 1 Pa, and the degraded anatase phase for 4 Pa (Fig. 1b). Here, the post-annealing didn't cause any drastic change in the mass densities (Fig. 1a), indicating that the short-range crystal structure has already been formed as deposited even though no diffraction peak was observed. It is said that the electron mobility of TiO_2 is highest in anatase phase due to the light electron mass [1]. Actually the $\mu_{\rm FE}$ of our TFTs showed the highest value at $P_{O2} = 1$ Pa, and was severely suppressed by the mixing of the rutile phase (0.1 Pa) or the degraded anatase phase (4 Pa).

The TiO₂ film deposited at 1 Pa was post-annealed at various T_a between 400 °C and 800 °C, and the transfer characteristics of the TFTs was evaluated. When T_a was increased from 400 °C to 600 °C, the ON current increased (Fig. 2a). The further increase in T_a , on the other hand, decreased the ON current. μ_{FE} was plotted as a function of T_a (Fig. 2b), showing the highest value of 8 cm²/Vs at $T_a = 600$ °C.

According to Fig. 2b, the electron mobility can reach comparable to that of single crystal films while the maladjustment of T_a rapidly decreases it by nearly one order of magnitude. Because the essential difference of the polycrystalline films from the single crystal films is the existence of grains and boundaries, their effect was investigated in detail. Our polycrystalline TiO₂ films had a triple-grain structure one inside another: A, the 10 µm scale grain with different crystal orientation (Fig. 3a), B, the 1 µm width grain with stripe shapes inside grain A (Fig. 3b), and C, the 0.1 µm scale grain inside grain B (FIg. 3c and d). Although grain A had no dependence on T_a, grain B and C were strongly influence by T_a as shown in FIg. 3e-i. When T_a is below 500 °C, the boundary of grain B or C is not clearly observed (Fig. 3e and f). On the other hand, as T_a was increased above 700 °C, the boundaries for grains B and C emerged and thickened (Fig. 3h and i). These observations indicate two structural factors which may define the elec-



Fig. 3 (a-d) Polycrystalline grains for TiO₂ films post-annealed at 800 °C, measured by (a) polarized light microscopy, (b,c) atomic force microscopy, and (d) conductive atomic force microscopy at 1 V. (e-i) Surface morphology of post-annealed TiO₂ films for T_a = (e) 400, (f) 500, (g) 600, (h) 700, and (i) 800 °C. "A", "B", and "C" represents three types of grains discussed in the sentence.

tron mobility in Fig. 2c: the grain growth or higher crystallinity which increases mobility, and the thicker grain boundary which scatters or blocks more electrons.

3. Conclusions

The structural factor was pointed out which has limited μ_{FE} in TiO₂-channel TFTs, especially related to the triple-grain structures of the TiO₂ films in the length scale from 0.1 µm to 10 µm. By optimizing the effect of grains and boundaries on the electron transport, μ_{FE} beyond 8 cm²/Vs was obtained, demonstrating that the electron mobility in the polycrystalline channel can reach comparable to that in the single crystalline film.

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References

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