酸化物半導体$MgIn_2O_4$を用いた新規な電界効果型トランジスタと置換ドーピングの効果

Novel Thin Film Transistors with Oxide Semiconductor $MgIn_2O_4$ with and without Substitutional Doping

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要　旨

酸化物半導体$MgIn_2O_4$を活性層に用いた新規な電界効果型トランジスタを作製した．更に，活性層に対する置換ドーピングの効果を検証し，活性層中のMgをAlで置換することによってキャリアの生成を効果的に制御できることを見出した．活性層にAlをドープしたTFTでは，ノーマリーオフの特性と高い移動度が両立する．また，従来の酸化物半導体TFTでは，半導体成膜時の酸素量に依存してTFT特性が敏感に変化することが問題となっているが，ドーピングによるキャリア制御を行うことで酸素量依存性が緩和され，広いプロセスマージンで高性能なTFTの作製が可能となることを示した．

ABSTRACT

Novel thin film transisters (TFT) with oxide semiconductor $MgIn_2O_4$ as an active layer were presented. We succeeded in controlling carrier generation in the active layer by substituting Al on Mg site. The doped TFT operated in normally-off mode with relatively high field-effect mobility. Furthermore, the characteristics of the doped TFT were less sensitive to the oxygen concentration during sputtering of the active layer. The doping enlarged the process margin and stabilized the TFT characteristics at high levels.

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1. Background

In recent years, liquid crystal displays (LCD), organic electro-luminescent (EL) displays, electronic paper, and the like have been made into practical use as flat panel displays (FPDs).

FPDs are driven by a driver circuit including a thin film transistor (TFT) having an active layer of amorphous silicon (a-Si) or polycrystalline silicon. These a-Si TFTs and polycrystalline silicon TFTs (particularly low temperature poly-crystalline silicon (LTPS) TFTs) have advantages and disadvantages. For example, although a-Si TFTs have good uniformity, they have disadvantages of insufficient mobility for driving a large screen LCD at a high speed, and a large shift of a threshold voltage in continuous driving. Although LTPS-TFTs have high mobility, they have a disadvantage in that threshold voltages largely vary due to a process for crystallizing an active layer by annealing using an excimer laser.

Thus, there is a demand for a novel TFT technology having combined advantages of a-Si TFT and LTPS-TFT. To satisfy these demands, a TFT with an oxide semiconductor, in which higher carrier mobility than amorphous silicon (a-Si) is expected, has been actively developed.

Specifically, after Nomura et al. disclosed a TFT using amorphous $InGaZnO_4$ (a-IGZO) that is capable of being deposited at room temperature and exhibits higher carrier mobility than a-Si,[1] numerous studies on amorphous oxide semiconductors having high carrier mobility have been extensively carried out.

In such amorphous oxide semiconductors, carrier electrons are generated by oxygen vacancy. Thus, oxygen concentration in a deposition process needs to be rigorously controlled. The characteristics of TFTs with the amorphous oxide semiconductor may easily result in a depletion mode when attempting to achieve high mobility. In addition, a process window may be too narrow to achieve a normally-off characteristic.

The control of the carrier generation is the key to achieve high performance TFTs. Here we present a novel TFT with $MgIn_2O_4$ (IMO) as an active layer, and a highly efficient method of controlling carrier generation: n-type substitutional doping.

2. Experimental Details and Results

2-1 A Novel IMO-TFT

For a channel material of TFT, we chose a compound $MgIn_2O_4$ (IMO) that was previously reported as a transparent conducting oxide.[2] The IMO crystal has a cubic inverse-spinel structure in which the two tetrahedral sites in the unit cell are occupied by In^{3+} and four octahedral sites are randomly occupied by Mg^{2+} and In^{3+}. A one-dimensional chain (a rutile chain) of edge-sharing InO_6 and MgO_6 octahedrons runs in various three-dimensional directions, and an InO_4 tetrahedron functions to connect the rutile chains. Since bottom of the conduction band is constituted by an isotropic 5s orbital of indium and lies at the Γ point, moving directions of the electrons are isotropic. The transporting characteristics of the carriers do not depend on the orientation of the film. Therefore, there is no disadvantage caused by the anisotropic property of the crystal structure, such as the case of ZnO with a wurtz type crystal structure.

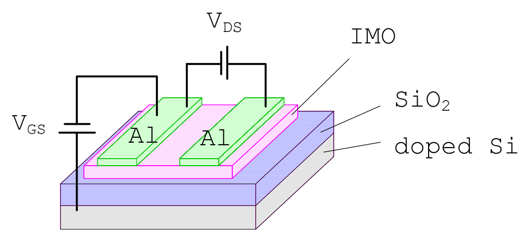

Fig.1 Schematic illustration of IMO-TFT.

For the TFT fabrication, we used a bottom gate and top contact configuration [see Fig.1] where the heavily doped Si served as the gate and the thermally oxidized SiO_2 layer (200 nm thick) served as the gate insulator. IMO was deposited to form an active layer with a thickness of 55 nm by DC magnetron sputtering via a metal mask using a $MgIn_2O_4$ sintered body target (Mitsui Mining & Smelting CO., LTD). An argon gas and an oxygen gas were introduced as a sputtering gas. The total pressure was fixed at 1.1 Pa, and the oxygen concentration was 2.0%. The first annealing was performed in air for one hour at 400°C to increase crystallinity. Next, Al was deposited by vacuum evaporation via a metal mask to form source and drain electrodes with thicknesses of 100 nm. A channel length was 50 µm, and a channel width was 400 µm. Finally, the second annealing was carried out in air at 300°C for an hour in order to improve adhesiveness and electric contact in an interface between the source and drain electrodes and the active layer.

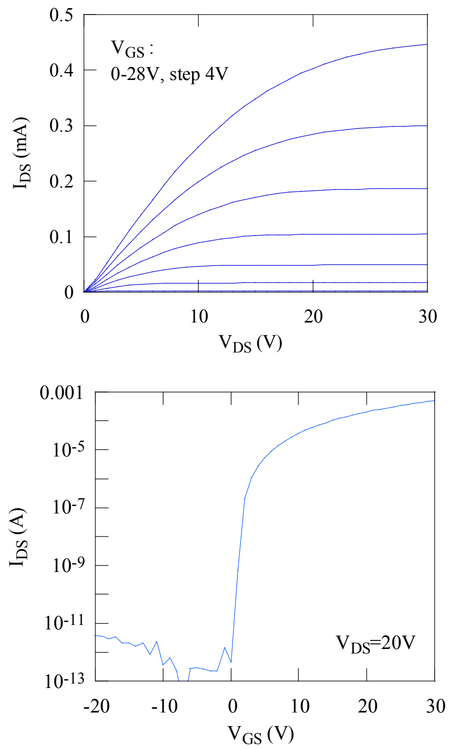

Fig.2 Typical (a) output and (b) transfer characteristics of IMO-TFT.

The typical output and transfer characteristics of IMO-TFT are shown in Fig.2. The IMO-TFT showed good characteristics with a field-effect mobility of 10.2 cm^2/Vs, an on-off current ratio over 10^8 and S-value of 0.11 V/dec.

2-2 Carrier Generation by Substitutional Doping

In order to control carrier generation in the active layer, we implemented the n-type substitutional doping. The carrier electrons are supposed to be generated when an n-type substituting cation having a larger valence is introduced into a substituted cation site. Here we chose Al as a dopant. The substitution of Al on Mg site forms a donor.

For the doping to work effectively, a host material needs to have a rigid structure (such as a spinel structure) and at least a short-range order of the crystal has to be maintained. In view of this aspect, IMO is a particularly preferable host material.

The TFTs discussed in this section were fabricated by the process similar to the one stated in section 2-1. The first annealing was not performed, so the highest temperature in the fabrication process was 300°C. The oxygen concentration during the sputtering process was 2.0%. For Al-doped IMO-TFT, a $Mg_{0.99}Al_{0.01}In_2O_4$ sintered body target (Mitsui Mining & Smelting CO., LTD) was used when sputtering an active layer.

In order to confirm the carrier generation by doping, transfer characteristics are compared in Fig.3 for the non-doped IMO-TFT and Al-doped TFT whose active layers were sputtered at the same oxygen concentration. It is well known that a TFT with higher carrier concentration has smaller V_{on}, the turn-on voltage at which the drain current starts to increase in the transfer curve. It is apparent from Fig.3 that the Al-doped active layer contained more carriers than the non-doped active layer did. Since the number of carriers generated by oxygen vacancy was assumed to be equivalent in the active layers sputtered at the same oxygen concentration, the excess carriers in the doped layer must be originated from the substitution of Al on Mg site.

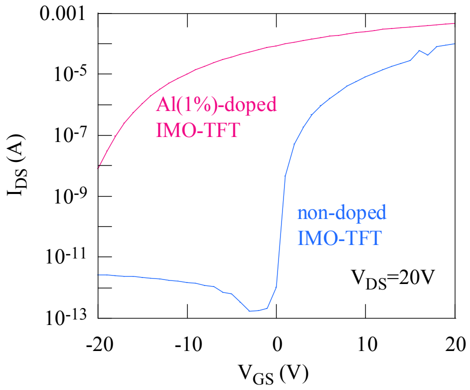

Fig.3 Transfer curves of non-doped IMO-TFT and Al(1%)-doped IMO-TFT. The active layers of both TFTs were sputtered at the oxygen concentration of 2.0%.

For comparison, transfer curves of non-doped a-IGZO-TFT and Sn-doped a-IGZO-TFT fabricated by the similar process as IMO-TFT are shown in Fig.4. On the contrary to the IMO case, doped IGZO-TFT had larger V_{on} meaning that the doping did not generate carriers. In cases of highly amorphous compounds such as IGZO, doping induces the local structural change and a stable local structure may be formed. Thus, carriers can not be generated effectively. In this case of IGZO, the affinity for oxygen of Sn resulted in larger V_{on} compared to the non-doped TFT.

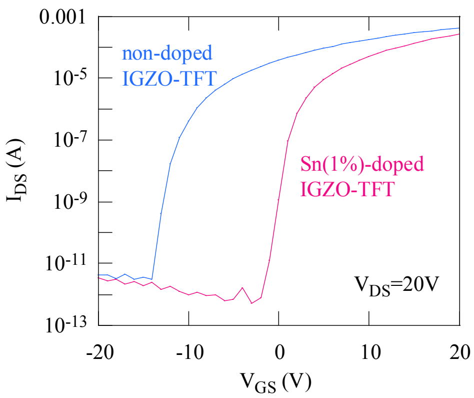

Fig.4 Transfer curves of non-doped IGZO-TFT and Sn(1%)-doped IGZO-TFT. The active layers of both TFTs were sputtered at the oxygen concentration of 2.0%.

2-3 Improved TFT Characteristics by Substitutional Doping

The TFTs discussed in this section were fabricated by the process similar to the one stated in section 2-1. The first annealing was not performed, so the highest temperature in the fabrication process was 300°C. The oxygen concentration during the sputtering process was varied as a parameter.

The oxygen concentration dependence of the transfer characteristics of non-doped IMO-TFTs and Al-doped IMO-TFTs are shown in Fig.5 and Fig.6, respectively. A relationship between the oxygen concentration and the field-effect mobility is illustrated in Fig.7.

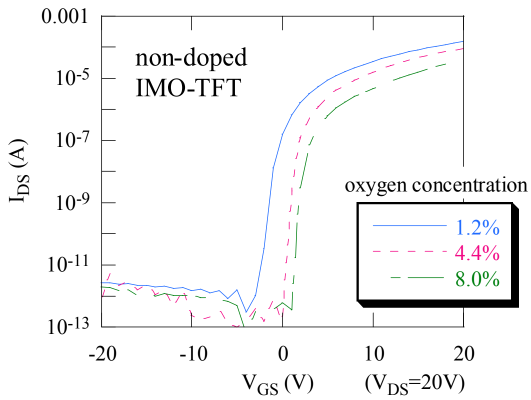

Fig.5 Transfer curves of non-doped IMO-TFTs. The active layers were sputtered at the oxygen concentration of 1.2%, 4.4% and 8.0%.

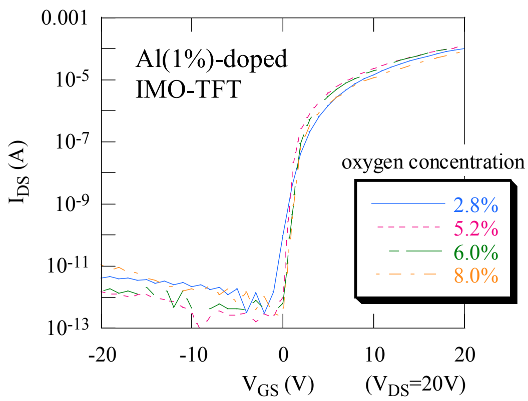

Fig.6 Transfer curves of Al(1%)-doped IMO-TFTs. The active layers were sputtered at the oxygen concentration of 2.8%, 5.2%, 6.0% and 8.0%.

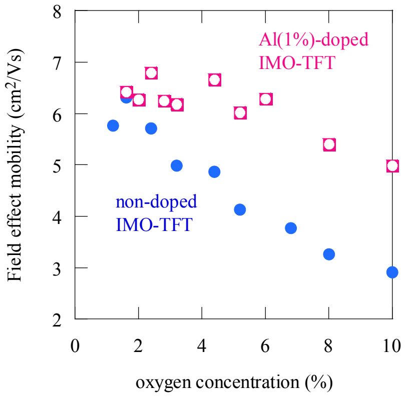

Fig.7 Relationship between oxygen concentration during sputtering and field effect mobility of non-doped and Al(1%)-doped TFTs.

For non-doped IMO-TFTs, the transfer characteristics strongly depended on the oxygen concentration. When the oxygen concentration increased, the oxygen vacancy in the active layer decreased, and so did the carrier concentration. Accordingly V_{on} increased and the normally-off operation was achieved with the oxygen concentration of 4.4% and higher. However, the field-effect mobility deteriorated for higher oxygen concentration as shown in Fig.7. In order to obtain a non-doped TFT with desired characteristics such as normally-off operation and maximum field-effect mobility, precise oxygen flow control during sputtering process is indispensable.

The Al-doped IMO-TFT showed excellent normally-off operation with a field-effect mobility of 6.0 cm^2/Vs and on-off current ratio over 10^8 at the oxygen concentration of 5.2%. Further, this excellent transfer characteristic was relatively maintained for higher oxygen concentration. The V_{on} scarcely shifted. The field-effect mobility was almost constant in the oxygen concentration range of 1.6 to 6.0%, and slightly decreased at 8% and more.

The characteristics of the doped-TFTs are less sensitive to the oxygen concentration, because the carriers are generated by Al substitution regardless of the oxygen concentration. Consequently, the excellent characteristics of high field-effect mobility and normally-off operation can be achieved in the wider range of oxygen concentration. The precise oxygen amount control is no longer necessary.

3. Conclusion

The novel IMO-TFT with a field-effect mobility of 10.2 cm^2/Vs and an on-off current ratio over 10^8 was presented. Since IMO has a cubic spinel structure and isotropy in the bottom of the conduction band, IMO-TFTs may have minimum characteristic variations and can be used in a large-size active matrix panel.

Furthermore, we introduced the n-type substituional doping to control carrier generation in the IMO active layer. The Al-doped IMO-TFTs showed improved characteristics of high field-effect mobility and normally-off operation in a wider process range compared to the non-doped TFT.

Other methods of controlling the carrier generation in oxides reported previously such as doping (not substitutional)[3, 4] and composition change[5] tend to result in a reduction of carrier mobility. With the substitutional doping method, we succeeded in controlling the carrier generation without any such drawbacks. The substitutional doping is essential to enlarge the process margin and stabilize the TFT characteristics at high levels.

References

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