G-5-02

Extended Abstracts of the 2019 International Conference on Solid State Devices and Materials, Nagoya, 2019, pp333-334

Low-temperature (150 °C) Processed Metal-Semiconductor Field-Effect Transistor with Hydrogenated In–Ga–Zn–O Stacked Channel

Yusaku Magari[1], S G Mehadi Aman[1], Daichi Koretomo[1], Kentaro Masuda[2], Kenta Shimpo[2] and Mamoru Furuta[1,2,3]

[1] Graduate School of Engineering, [2] Materials and Science and Technology Course, [3] Center for Nanotechnology

Kochi University of Technology, Tosayamada, Kami city, Kochi 782-8502, Japan

Tel: +81-887-57-2521 E-mail: 216007n@gs.kochi-tech.ac.jp

Abstract

We developed low-temperature (150 °C) processed metal-semiconductor field-effect transistors (MES-FETs) with a stacked In–Ga–Zn–O (IGZO) channel consisting of hydrogenated IGZO on conventional IGZO. The hydrogenated IGZO was prepared by introducing H_2 gas into Ar and O_2 gases during the sputtering deposition. The proposed MES-FET (W/L = 100/10 µm) with a stacked channel improved on-current up to 313 µA combined with a large $I_{on/off}$ ratio of 4.2×10^8. The obtained results indicate that the stacked channel will not be only effective to improve Schottky properties but also to induce an electron confinement effect at the interface between hydrogenated IGZO and conventional IGZO.

1. Introduction

Amorphous oxide semiconductors (AOSs), particularly In–Ga–Zn–O (IGZO) have received much attention due to their superior electrical properties (μ_{FE} > 10 $cm^2V^{-1}s^{-1}$) even deposited at room temperature [1]. Therefore, they are considered to be promising to develop future flexible devices. We previously reported that post-annealing temperature for defect reduction of IGZO thin-film transistors (TFTs) can be reduced from 300 to 150 °C by adding hydrogen during the IGZO sputtering, which is lower than the softening temperature of flexible plastic substrates [2]. However, a reliability of low-temperature processed IGZO TFT is still challenging issue. In contrast, metal-semiconductor field-effect transistors (MES-FETs) have several advantages such as low operation voltages due to lack of an insulator layer, while Schottky gate can be formed at low temperature process. Thus, the IGZO MES-FETs is a good candidate for flexible device applications. However, there are a few reports for AOSs based MES-FETs due to a difficulty of the formation of stable and good Schottky contacts with AOSs [3,4].

In this study, we propose a method to improve electrical performance of an IGZO MES-FET by employing a stacked IGZO channel consisting of hydrogenated IGZO on conventional IGZO films.

2. Experimental method

A top-gate and coplanar MES-FET was fabricated on a glass substrate as shown in Fig. 1(a). First, a 50- or 200-nm-thick IGZO film was deposited by DC magnetron sputtering without substrate heating from a ceramic $InGaZnO_4$ (In:Ga:Zn = 1:1:1 atom.%) target using mixtures of Ar, O_2, and H_2. The O_2 and H_2 gas ratios were defined as $R[O_2] = O_2/(Ar+O_2+H_2)$ and $R[H_2] = H_2/(Ar+O_2+H_2)$, respectively. Two types of active channels were formed as shown in Fig. 1(b). For a 200-nm-thick Ar+O_2-sputtered IGZO channel, R[O_2] was varied from 0.33 to 0.80%. For a 50-nm-thick stacked IGZO channel, Ar+O_2+H_2-sputtered IGZO with R[H_2] of 5% was deposited on 25-nm-thick Ar+O_2 sputtered IGZO film. After patterning of the IGZO channels by photolithography and wet etching, the films were annealed in air at 150 °C for 1 hour. Then, a 120-nm-thick Ag_xO for Shcottky gate was deposited by RF reactive sputtering, and an Au was deposited by vacuum evaporation. Finally, source and drain electrodes were formed by Mo. Gate, source, and drain electrodes were patterned by photolithography and liftoff. Channel length (*L*) and width (*W*) were 10 and 100 µm, respectively.

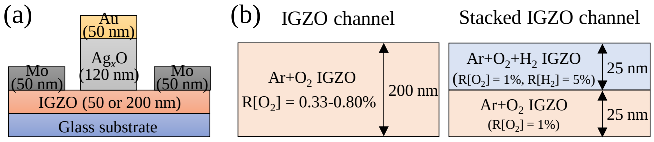

Fig. 1 (a) Schematic cross-sectional view of the IGZO MES-FET and (b) Two types of IGZO channels used in the experiments.

3. Results and discussion

Figure 2 shows the transfer characteristics of the IGZO MES-FET with a 200-nm-thick homogeneous IGZO channel deposited at different R[O_2]. Solid and dash lines show the drain and gate current, respectively. Turn-on voltage (V_{on}) of the MES-FET with R[O_2] of 0.80% was around 0 V. In general, the V_{on} of MES-FETs should be controlled in negative gate voltage (V_{gs}) since electrons flow to the gate when V_{gs} exceed built-in potential (V_{bi}) of Schottky contact. By decreasing the R[O_2] to 0.66%, V_{on} shifted to negative V_{gs}, while off-currents (I_{off}) increased significantly. Furthermore, no field effect was observed at R[O_2] of 0.33%. The increase of I_{off} was related to an increase in I_{gs} of the Schottky junction as shown in Fig. 2.

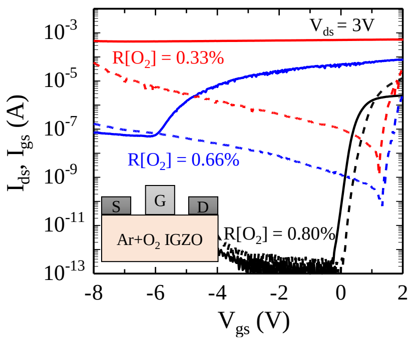

Fig. 2 Transfer characteristics of the MES-FETs with IGZO channels deposited at various R[O_2]. Solid and dashed lines show I_{ds} and I_{gs}, respectively.

Figure 3(a) shows Hall carrier concentration (N_e) of the IGZO films as a function R[O_2]. N_e was 9.6×10^{16} cm^{-3} for the IGZO film deposited at R[O_2] of 0.80%. N_e increased by approximately an order from 9.6×10^{16} to 1.7×10^{18} cm^{-3} when R[O_2] decreased from 0.80 to 0.33%, suggesting that oxygen vacancies were created by decreasing R[O_2]. Based on the obtained N_e, the depletion layer width (W_d) in the IGZO film can be calculated using Eq. (1)

$$W_d\left(V_{gs}\right)=\sqrt{\frac{2\varepsilon_s\varepsilon_0}{eN_e}\left(V_{bi}-V_{gs}\right)} \qquad (1)$$

where ε_s is the relative permittivity of IGZO, which was taken to be 13.5 [4], ε_0 is vacuum permittivity, and e is the unit charge. V_{bi} of 0.45 V that obtained from capacitance-voltage measurement of Schottky diodes was used.

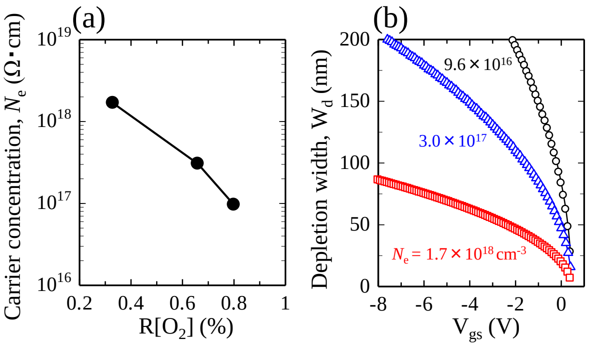

Fig. 3 (a) N_e of the IGZO film as a function of R[O_2], and (b) W_d in the IGZO film with various N_e.

Figure 3(b) depicts the theoretical values of W_d in IGZO films with various N_e. We can estimate the V_{on} of MES-FET from the V_{gs} where W_d is equal to the channel thickness (200 nm). The estimated V_{on} for 200-nm-thick IGZO channels were -2.1 V for N_e of 9.6×10^{16} and -7.4 V for 3.0×10^{17} cm^{-3}. These values are correlated well the V_{on} of the MES-FETs as shown Fig. 2. We controlled V_{on} by varying R[O_2] that influences on N_e. However, a slight difference in R[O_2] strongly affected the N_e of IGZO, result in deterioration of Schottky diodes and I_{off} of the MES-FETs.

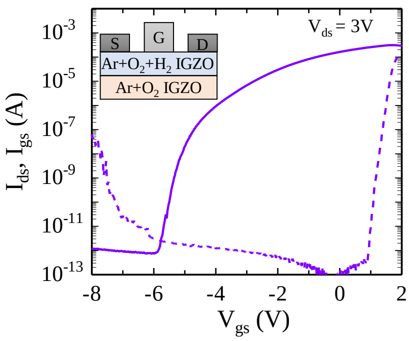

Fig. 4 Transfer characteristic of the MES-FET with an Ar+O_2- and Ar+O_2+H_2-sputtered stacked IGZO channel.

Figure 4 shows the transfer characteristic of the MES-FET with a stacked IGZO channel. By means of forming the 25-nm-thick Ar+O_2+H_2-sputtered IGZO on 25-nm-thick Ar+O_2-sputtered IGZO, transfer characteristic of the MES-FET was markedly improved as compared with conventional Ar+O_2-sputtered IGZO channel. The V_{on}, on-currents (I_{on}), and on-off current ratios ($I_{on/off}$) of MES-FETs with the stacked channel were -5.9 V, 3.1×10^{-4} A, and 4.2×10^{8}, respectively. It should be noted that although N_e of stacked IGZO is 1.3×10^{19} cm^{-3}, the MES-FET maintained low I_{off} of 7.4×10^{-13} A.

Figure 5 shows Tauc plots of optical absorption spectra of Ar+O_2- and Ar+O_2+H_2-sputtered IGZO films. The band gap (E_g) of 3.04 eV was obtained for the Ar+O_2-sputtered IGZO film, whereas a remarkable increase of E_g to 3.22 eV was observed for the Ar+O_2+H_2-sputtered IGZO film. An ionization potential of the IGZO films were measured by photoelectron yield spectroscopy; however, no noticeable difference was observed from both films (data not shown). These results suggest that an energy gap of about 0.18 eV exists between the conduction band energy levels of the Ar+O_2- and Ar+O_2+H_2-sputtered IGZO films. Therefore, this energy gap probably acts as an electron confinement at channel interface between two stacked hydrogenated IGZO layers of MES-FET.

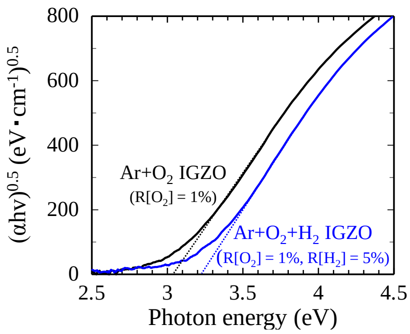

Fig. 5 Tauc plots of Ar+O_2- and Ar+O_2+H_2-sputtered IGZO films.

4. Conclusions

In this work, we have investigated the electrical properties of MES-FETs with a stacked channel consisting of hydrogenated IGZO on conventional IGZO at low-temperature process. The I_{on} of the stacked IGZO channel was markedly improved more than 30 times compared with conventional Ar+O_2-sputtered IGZO MES-FETs. Moreover, V_{on} achieved -5.9 V, while I_{off} decreased to 7.4×10^{-13} A. The E_g of IGZO film increased from 3.04 to 3.22 eV by introducing hydrogen during sputtering, suggesting that an electron confinement effect was induced at the stacked channel interface, which led to high-I_{on} of the MES-FETs. To achieve both of the high-$I_{on/off}$ and appropriate V_{on} among oxide semiconductor MES-FETs, a stacked channel would be a promising approach.

Acknowledgements

This work was supported in part by JSPS KAKENHI Grant Number 16K06309.

References

[1] K. Nomura *et al*., *Nature* **432** (2004) 488.
[2] S G M. Aman *et al*., *Appl. Phys. Express* **11** (2018) 081101.
[3] G. T. Dang *et al*., *IEEE Electron Device Lett*. **36** (2015) 5.
[4] D. H. Lee *et al*., *ECS Solid State Lett*. **1** (2012) 1.