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Fabrication and Properties of Amorphous In–Ga–Zn–O Material and Transistors

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In–Ga–Zn–O thin films were fabricated by means of reactive RF magnetron sputtering. Mechanism of free electrons generation via oxygen vacancies formation is proposed to determine the relationship between oxygen content in the deposition atmosphere and the transport properties of IGZO thin films. The depletion-mode a-IGZO thin film transistor with field-effect mobility of 12 $\mathrm{cm^2/(V\,s)}$ has been demonstrated.

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1. Introduction

Amorphous In–Ga–Zn–O (a-IGZO) is regarded as one of the most promising materials among transparent amorphous oxide semiconductors (TAOS), owing to: carrier mobility above 5 $\mathrm{cm^2/(V\,s)}$, one order higher of magnitude compared to conventional amorphous semiconductors, such as amorphous Si (a-Si); potential to control carrier concentration in the range of several orders of magnitude, yielding thin films from insulating to highly conducting ones; room-temperature fabrication and processing, and high transparency in the visible wavelength region. An unique aspect of TAOS is that the carrier mobility is not sensitive to the thin film microstructure, as is case of conventional covalently-bonded semiconductors. This fact arises from the nature of the chemical bonding in these $(n-1)d^{10}ns^0$ $(n \geq 4)$ metal oxides. Carrier transport in covalently-bonded materials, such as Si, is carried out primarily through anisotropic sp^3 orbitals, so that introducing randomness into the structure greatly reduces bond overlap and carrier mobility. In TAOS, the higher ionicity of the bonding leads to a conduction band formation on spherical s orbitals. Because the overlap of s orbitals is not significantly altered by the introduction of structure randomness, carrier transport and, thus, mobility is insensitive to the amorphization [1].

All this facts turn a-IGZO to become a key material for next generation electronic devices, in particular for thin-film transistors (TFT), challenging silicon not only in conventional applications but opening possibilities to totally new areas, like electronic paper or ultrahigh-resolution displays for biomedical applications.

Several research groups have already demonstrated the possibility of fabrication a-IGZO thin films by using such techniques as pulsed laser deposition, sol–gel, dc and rf magnetron sputtering. Reported a-IGZO thin films exhibit optical transmission above 75%, mobility exceeding 9 $\mathrm{cm^2/(V\,s)}$ and possibility to control of carrier concentration in the range from 10^{14} to 10^{20} $\mathrm{cm^{-3}}$. Among the devices presented in the literature, the most relevant electrical properties of reported a-IGZO TFT are: μ_{FE} in range of 5 to 36 $\mathrm{cm^2/(V\,s)}$, an on-off current ratio ranging between 10^4 and 10^8, and a threshold voltage in range of 0.6 to 5.90 V. The parameters of the reported films are affected by preparation conditions, including deposition method, atmosphere during deposition and pressure [2].

However, in spite of the promising properties offered by a-IGZO, there is still a significant challenge aiming to explain the mechanism of free carrier generation in this multicomponent oxide. Adjustment of transport properties of a-IGZO thin films and devices is achieved by controlling material defect structure, namely generation of oxygen vacancies ($\mathrm{V_O}$) during the thin film growth. This can be achieved by varying the oxygen content during deposition process. Still, much of the debate surrounding this issue is related to the precise role of oxygen vacancies and indicated that $\mathrm{V_O}$ may act as electron donors in a-IGZO, or as deep electron trap states localized into the band gap [3]. Therefore, understanding the role of these native point defects is key toward controlling the transport properties of a-IGZO.

In this work, we report on the fabrication and properties of a-IGZO thin films deposited by RF reactive magnetron sputtering and analyse the mechanism of carrier generation. Finally, we present the TFT with the a-IGZO active layer with performance being improved to actual state of the art of conventional a-Si devices.

2. Experimental details

IGZO thin films with a thickness of 70 nm were deposited on unheated quartz substrates, by a reactive RF

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magnetron sputtering in Ar/O_2 plasma in Leybold Z400 system, from 75 mm diameter ceramic $InGaZnO_4$ target of 4N purity, at a pressure (P_{tot}) of 0.85 Pa. The oxygen content (%O_2) in sputtering atmosphere was varied between 0% and 0.9%. The RF power was maintained on level 50 W. The composition of IGZO films was inferred from the Rutherford backscattering spectrometry (RBS) using 2 MeV He^+. To facilitate precise measurements of composition, complementary IGZO films were deposited on (111)-oriented Si substrate. The analysis was based on SIMNRA program. Structural analysis was performed using Philips X'Pert Pro Alpha1 Multi Purpose Diffractometer. The surface morphology was examined with scanning probe microscopy (SPM) using a Veeco Innova instrument. The resistivity of thin films was determined from four-point probe measurements with JANDEL RM3-AR apparatus. Carrier type, concentration and mobility were evaluated from the Hall measurements in the van der Pauw configuration at magnetic field of 0.44 T, by means of a Phys Tech RH2035 setup. Ohmic contacts were made by sputter deposition of Ti/Au bilayer. For optical characterization transmittance measurements in the wavelengths range 250–950 nm, by means of a SENTECH SE800E spectroscopic ellipsometer were performed.

For the TFT fabrication, a Ti/Al (15/45 nm) metallization, sputter-deposited and patterned using lift-off process was used as gate, source and drain electrodes. 100 nm thick SiO_2 layer was fabricated by the plasma enhanced chemical vapor deposition technique. SiO_2 was chosen as gate dielectric due to its high band gap (9 eV) and large band offsets with IGZO layer, resulting in negligible gate leakage current. 50 nm thick a-IGZO films were deposited under $P_{tot} = 0.85$ Pa, %O_2 = 0.88% and $P_{RF} = 50$ W, and patterned to form channel 100 μm long and 10 μm wide. The electrical characterization including current–voltage measurement of transfer ($I_{DS} = f(V_{GS})$) and output ($I_{DS} = f(V_{DS})$) characteristics of transistors was carried out in the dark by using a Keithley SMU236/237/238 I–V measurement system.

3. Results and discussion

The IGZO thin films deposited in pure Ar atmosphere and at atmosphere with oxygen content from 0.25% to 0.65%, have atomic concentration of $In_{1.5}Ga_{1.7}ZnO_6$ and $In_{1.5}Ga_{1.6}ZnO_6$, respectively. Surprisingly, the oxygen-deficient IGZO thin films, with atomic concentration of $In_{1.7}Ga_{1.7}Zn_{1.3}O_3$, were formed during deposition under 0.9% O_2. Moreover, all IGZO films independent of the oxygen content in the deposition atmosphere show Zn deficiency. The roughness of a-IGZO surface, analyzed on a 1×1 μm^2 area by SPM was 0.5 nm to 0.6 nm. The transmittance of all films increases from 75% to 90% for wavelengths from 350 to 900 nm. The band-gap energy evaluated by Taucs method is varying from 3.8 eV to 3.45 eV.

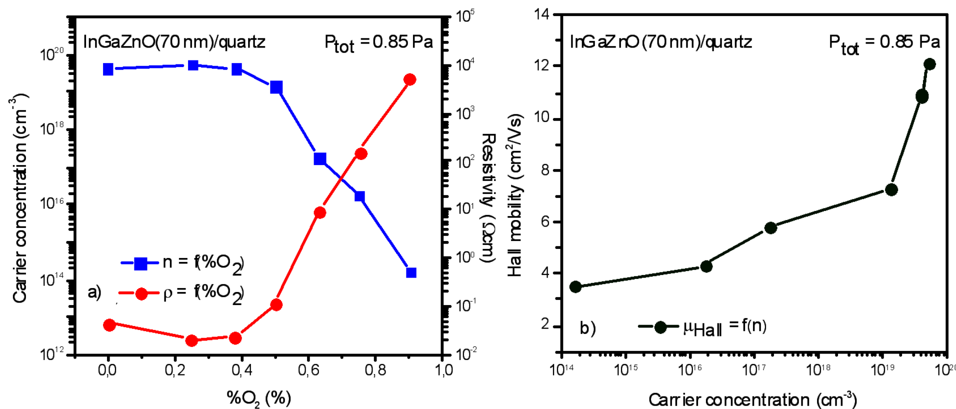

Fig. 1. Carrier concentration and resistivity of a-IGZO as a function of %O_2 (a) and dependence of Hall mobility on the carrier concentration in a-IGZO (b).

Figure 1a shows carrier concentration and resistivity of the a-IGZO films as a function of the oxygen content in the deposition atmosphere. The carrier concentration is 6×10^{19} cm^{-3} for the films deposited in oxygen-free atmosphere, then decreases to 1×10^{14} cm^{-3} for the films fabricated at 0.9% O_2. In these conditions the resistivity of a-IGZO films increased almost six orders of magnitude. The increase of the oxygen content in the deposition atmosphere contributes to filling the oxygen vacancies arisen in the film, leading to a reduction of the carrier concentration, which allow to invoke them as sources of n-type conductivity in a-IGZO, arguing the hypothesis that free electrons originate from these point defects. Figure 1b shows that the Hall mobility of a-IGZO increases in function of carrier concentration and reaches 12 cm^2/(V s) above $n = 1 \times 10^{19}$. This trend is opposite to that for polycrystalline semiconductors in which carrier scattering with dopant ions controls the mobility, and is a consequence of different transport mechanism. In a-IGZO, below the critical value of n, carrier trans-

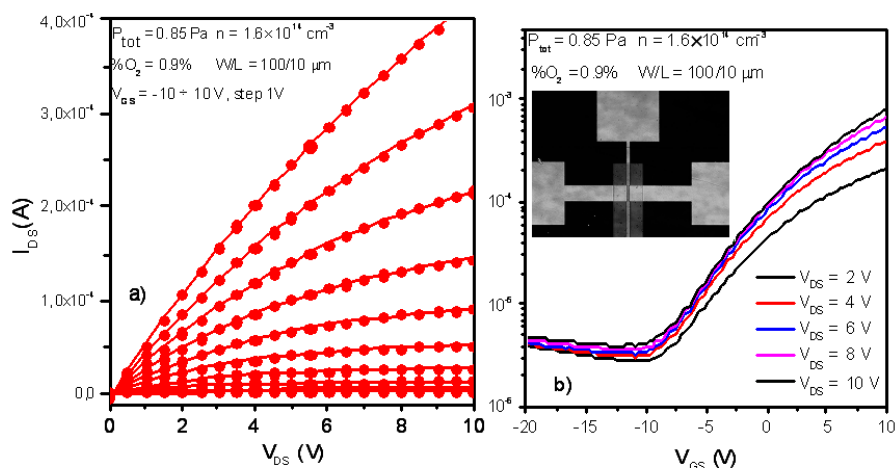

Fig. 2. The output (a) and transfer (b) characteristics of the a-IGZO TFT.

port takes place by percolation through distribution of potential barriers around the conduction band edge derived from the structural randomness of the oxide thin films. Therefore, the decrease of the oxygen content in the sputtering chamber leads to a-IGZO films with a higher number of oxygen vacancies thus, a higher level of carrier concentration, and consequently to a shift of the Fermi level toward the conduction band.

In Fig. 2 we depict the output and transfer characteristics of TFT with a-IGZO active layer fabricated at $P_{\rm tot} = 0.85$ Pa and 0.9% O_2. The device operates in a depletion mode following the standard TFT theory, with threshold voltage of -6.5 V, and showing pitch-off region. The field-effect mobility evaluated from the saturation region of 12 $\mathrm{cm}^2/(\mathrm{V\,s})$, which is larger by an order of magnitude as compared to a-Si TFT, and similar to a-IGZO TFT reported in the literature [2]. The current on-to-off ratio equals 3×10^2 A/A, which is at least two orders of magnitude lower than results reported up today [2, 3] and indicates that channel is not fully depleted in the off state.

4. Conclusions

Transparent, amorphous IGZO thin films were fabricated by reactive RF magnetron sputtering and characterized by use of complementary methods of compositional and microstructural analysis. This made it possible to demonstrate a relationship between atomic composition, microstructure and transport properties of the a-IGZO films. The oxygen content in the deposition atmosphere remarkably affects the electrical properties of a-IGZO, and directly deals with the oxygen vacancies in the films. Increasing of oxygen content decreases the carrier concentration and the Hall mobility. Modification of these parameters also enables to vary the resistivity of the films over several orders of magnitude, which suggests that the oxygen vacancies act as shallow donors in a-IGZO. The bandgap energy of a-IGZO is in the range of 3.8 eV to 3.45 eV.

Furthermore, we have demonstrated the TFT with a-IGZO active layer, showing $\mu_{\rm FE}$ higher by one order of magnitude, compared to a-Si.

Acknowledgments

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