Fabrication of oxide-gate thin-film transistors using PECVD/PLD multichamber system

N. Matsuki,1, J. Ohta, H. Fujioka, M. Oshima, M. Yoshimoto, H. Koinuma

Abstract

We developed a new multichamber system which combines a pulsed-laser deposition (PLD) and a plasma-enhanced chemical vapor deposition (PECVD) with shadow masks installed to define the film deposition area on a substrate. In order to verify the capability of this PLD/PECVD multichamber system, hydrogenated amorphous silicon (a-Si:H) thin film transistors (TFTs) using MgO and Al2O3 gate dielectrics have been fabricated on glass/indium-tin-oxide (ITO) substrates. The MgO and Al2O3 films fabricated on fused silica substrates by PLD exhibited transparency higher than 90% and a low leakage current (1 nA/cm² at 1 MV/cm). After depositions of the MgO or Al2O3 film on the glass/ITO, the sample was transferred to the PECVD chamber for a-Si:H deposition without exposing them to the air. TFTs thus fabricated exhibited such high characteristics as the threshold voltage ($V_{TH}$) as low as 0.35 V and gate bias dependence of source-drain current exceeding five orders of magnitude. The results indicate a high quality a-Si:H/oxide interface and that heterojunction devices can be produced by using the PLD/PECVD multichamber system.

Keywords: Thin-film transistor; MgO; Al2O3; Amorphous silicon; Plasma enhanced chemical vapor deposition; Pulsed laser deposition

1. Introduction

Recently, pulsed laser deposition (PLD) has been used to deposit various kinds of thin films [1,2] including oxides, nitrides, semiconductors, metals, carbon-related materials and inorganic materials. The advantages of the PLD technique are as follows: (1) even the materials with high melting point can become thin film easily by PLD because pulsed laser has a very high energy ($\sim 10^8$ W/cm²); (2) contaminations coming from filaments used for heating up source materials can be avoided; (3) gas pressure for reaction (oxidation, reduction, nitrification, etc.) during depositions can be controlled from ultra-high-vacuum (UHV) to atmospheric pressure; (4) compositional differences between the source materials and the deposited film are quite small because diffusion in the source materials can be neglected owing to the very short ablation time. On the other hand, plasma enhanced chemical vapor deposition (PECVD) has been used for depositions of hydrogenated amorphous silicon (a-Si:H), amorphous silicon nitride (a-SiN:H), and amorphous silicon germanium (a-SiGe:H) as well as, amorphous silicon dioxide (a-SiO2), and microcrystalline silicon ($\mu$-c-Si) related materials [3–11]. PECVD is feasible for low temperature, wide area depositions. Thus, PECVD is now mainly used for productions of thin-film transistors for liquid crystal displays and solar cells on glass substrates.

If we can combine the PECVD and PLD techniques, various kinds of new hybrid materials will be produced. As a first step, we fabricated thin-film transistors (TFTs) with a-Si:H/PLD-oxide insulator interfaces using a newly developed PLD/PECVD multichamber system in order to evaluate the quality of the interfaces. There have been many studies on a-Si:H insulator structures directed towards thin-film transistor (TFT) applications. Most researchers have utilized a-SiN:H as a dielectric material for the a-Si:H TFTs, because it offers a low interface defect density near the conduction band edge. To reduce on-state voltage, the use of gate dielectric with a higher dielectric constant than a-SiN:H is highly desired. Metal oxides are promising candidates for this purpose. However, good a-Si:H TFTs using metal oxides have scarcely been reported except for
the case of SiO$_2$. Yi and coworkers attempted the fabrication of a-Si:H TFTs using RF-sputtered BaTiO$_3$ and MgO as gate insulators and reported large leakage current in the oxide films [12]. One remedy to solve this problem is the use of double-layer gate dielectrics such as Ta$_2$O$_5$/a-Si:N:H, Al$_2$O$_3$/a-Si:N:H [13,14], and MoTaO$_x$/SiO$_x$/a-SiN:H [15]. In these structures, low leakage currents and low a-Si:H/insulator interface defect densities were assured by the use of the a-SiN:H layer. However, double layer structures always lead to low effective dielectric constants.

In this paper, we present the details about structure of the PECVD/PLD multichamber and its applications to the fabrication of TFTs with MgO or Al$_2$O$_3$ gate-insulators.

2. Experimental

In order to fabricate a-Si:H/metal oxide structures, we have developed a new system consisting of PLD and PECVD chambers, which is schematically illustrated in Fig. 1. Samples can be transferred from one chamber to another without being exposed to the air. This in situ sequential deposition was essentially important to obtain a clean a-Si:H/insulator interface. The PLD chamber (PASCAL Co. Ltd) with a diameter of 32 cm and height of 55 cm is evacuated by a turbo molecular pump (evacuation speed 250 l/s) and the base pressure is maintained at $5 \times 10^{-9}$ Torr. Samples set in the PLD chamber can be heated up to 800$^\circ$C by an infrared lamp heater. A pair of PE-PECVD chambers (KITANO SEIKI Co. Ltd) with a diameter of 21 cm and a height of 29 cm are installed, respectively with a turbo molecular pump (evacuation speed 150 l/s) to keep the base pressure below $5 \times 10^{-8}$ Torr. Substrates placed in a PEPECVD chamber can be heated up to about 500$^\circ$C by a heater buried in the anode electrode.

MgO and Al$_2$O$_3$ films were deposited on ITO (Indium tin oxides) coated glass substrates in the PLD chamber at temperatures ranging from room temperature to 400$^\circ$C. O$_2$ ambient pressures were $5 \times 10^{-6}$ Torr for MgO and $1 \times 10^{-4}$ Torr Al$_2$O$_3$ films, respectively. A Lambda Physik COMPex 102 excimer laser generator provided 20 ns pulses of 248 nm (KrF) radiation. The laser was focused by a quartz lens and irradiated onto a commercially obtained polycrystalline MgO or Al$_2$O$_3$ target ($7.0$ J/cm$^2$, 10 Hz). For the leakage current and capacitance measurements on the MgO and Al$_2$O$_3$ films, 200 $\mu$m$\phi$ aluminum spot electrodes were deposited by vacuum evaporation (ULVAC VPC-250).

Inverse staggered TFTs were fabricated on MgO or Al$_2$O$_3$/ITO/glass. a-Si:H was deposited on the oxide films with SiH$_4$ flow rate of 10 sccm and a RF power density of 50 mW/cm$^2$. Then, aluminum electrodes for source and drain were deposited by thermal evaporation with a metal patterned mask.

3. Results and discussion

Fig. 2 shows a cross-sectional structure of the TFTs. For simplicity in processing, n-type source/drain contact layers were not employed for these devices. The dark- and photo-conductivity of the a-Si:H films were $7 \times 10^{-11}$ and...
7 × 10⁻⁶ Ω⁻¹ cm⁻¹, respectively. Hydrogen contents and optical band gap of the a-Si:H films measured by IR and UV–visible spectroscopy were 13% and 1.7 eV, respectively. Leakage currents through oxide dielectrics were measured between the Al top electrode and ITO. The leakage current is reduced with increasing substrate temperatures. Hence, we set the growth temperature at 400°C for the use of glass substrates. Fig. 3 shows the current density vs. electric field (\(J-E\)) characteristics of the leakage currents through 400 nm thick \(\text{Al}_2\text{O}_3\) and \(\text{MgO}\) films grown by PLD. The leakage current density for both oxide films at an electric field of 1 MV/cm is 1 nA, which is low enough to fabricate TFTs. The field dependence of the leakage current is rather small, which indicates that Fowler–Nordheim current is not a dominant conduction mechanism, but there is a possibility of Poole–Frankel conduction [16]. Average relative dielectric constants for the \(\text{Al}_2\text{O}_3\) and \(\text{MgO}\) films were measured with an LCR meter are 7.8 and 10.8, respectively. Fig. 4 shows the optical transmittance of \(\text{Al}_2\text{O}_3\) and \(\text{MgO}\) films deposited on quartz substrates. Thickness of the \(\text{Al}_2\text{O}_3\) and \(\text{MgO}\) films used for these measurements were 400 and 360 nm, respectively. Both \(\text{Al}_2\text{O}_3\) and \(\text{MgO}\) films show transmittance larger than 90% for the visible and UV light with the wave lengths longer than 250 nm. This result indicates that these films have nearly stoichiometric composition. X-ray diffraction measurements of the MgO and \(\text{Al}_2\text{O}_3\) films deposited on fused silica substrates reveal that these films are randomly oriented poly-crystalline materials and their average grain size is approximately 20 and 37 nm, respectively.

Fig. 5 shows the transfer characteristics of the TFTs with the \(\text{Al}_2\text{O}_3\) and \(\text{MgO}\) insulators at the drain voltage, \(V_D\) = 10 V and Fig. 6 shows the output characteristics of the TFT with the MgO insulator. The on/off drain current ratios for the \(\text{Al}_2\text{O}_3\) and \(\text{MgO}\) TFTs are \(2.8 \times 10^5\) and \(6.7 \times 10^5\), respectively. We believe that these values can be further improved by the use of n-type contact layers, which we eliminated for the simplicity of fabrication process in the present experiment. The threshold voltage for the MgO TFT is as low as 0.35 V, which is indicative of low fixed charge density. This low threshold voltage is useful in lowering the operational voltage. The interface state densities estimated with the subthreshold swing [17] are \(2-3 \times 10^{12}\) cm⁻² for these TFTs.

4. Conclusions

We have demonstrated that the use of the PLD/PECVD multichamber system makes it possible to fabricate single metal oxide gate insulator TFTs. The leakage current densities both through the MgO and \(\text{Al}_2\text{O}_3\) films were approximately 1 nA/cm² at 1 MV/cm. We have observed successful operations for both the TFTs with the MgO and \(\text{Al}_2\text{O}_3\) gate insulators fabricated in this PLD/PECVD system. The TFT with the MgO gate insulator exhibited a performance slightly superior to that with the \(\text{Al}_2\text{O}_3\). Although further optimizations are required to obtain device-grade TFTs, we have verified the possibility to apply the PLD/PECVD multichamber system to the fabrication of TFTs and a-Si:H/PLD-oxide hybrid materials.
References

[1] R. Singh (Ed.), Advances in laser ablation of materials, Mat. Res. Soc. Proc., San Francisco (1998).
[2] Laser Ablation and Deposition, in: J. Miller, R. Haglund (Eds.), Experimental Method in the Physical Sciences, vol. 30, Academic Press, New York, 1997.
[3] R. Street (Eds.), Technology and Applications of Amorphous Silicon Springer Series in Material Science, vol. 37, Springer, Berlin, 1999.
[4] P. Taylor, M. Thompson, P. LeComber, Y. Hamakawa, A. Madan (Eds.), Amorphous Silicon Technology, Mater. Res. Soc. Proc. 192 (1990).
[5] A. Madun, Y. Hamakawa, M. Thompson, P. Taylor, P. Le Comber (Eds.), Amorphous silicon technology, Mater. Res. Soc. Proc. 219 (1991).
[6] M. Thompson, Y. Hamakawa, P. Le Comber, A. Madan, E. Schiff (Eds.), Amorphous silicon technology, Mater. Res. Soc. Proc. 258 (1992).
[7] E. Schiff, M. Thompson, A. Maden, K. Tanaka, P. Le Comber (Eds.), Amorphous silicon technology, Mater. Res. Soc. Proc. 297 (1993).
[8] M. Hack, E. Schiff, M. Powell, A. Matsuda, A. Madan (Eds.), Amorphous silicon technology, Mater. Res. Soc. Proc. 377 (1995).
[9] M. Hack, E. Schiff, S. Wagner, R. Schropp, A. Matsuda (Eds.), Amorphous silicon technology, Mater. Res. Soc. Proc. 420 (1996).
[10] S. Wagner, M. Hack, E. Schiff, R. Schropp, I. Shimizu (Eds.), Amorphous and Microcrystalline silicon technology, Mater. Res. Soc. Proc. 467 (1997).
[11] H. Bran, R. Collins, H. Okamoto, S. Guha, R. Schropp. Amorphous and Heterogeneous Silicon Thin Films: Fundamentals to Devices. Mat. Res. Soc. Proc. 557 (1999).
[12] J. Yi, R. Wallace, N. Sridhar, D.D.L. Chung, W.A. Anderson. Mater. Res. Soc. Proc. 321 (1994) 701.
[13] T. Tsukada. Mater. Res. Soc. Proc. 284 (1993) 371.
[14] H. Yamamoto, H. Matsumaru, K. Shirahashi, M. Nakatani, A. Sasano, N. Konishi, K. Tsutsui, T. Tsukada, Tech. IEDM Dig. Dec., 1990, p. 851.
[15] Y. Fujimoto, IBM J. Res. Develop. 36 (1992) 76.
[16] M.S. Sze, Physics of Semiconductor Devices, 2 ed., Wiley, New York, 1981 (p. 497).
[17] A. Rolland, J. Richard, J.P. Kleider, D. Mencaragia, J. Electrochem. 140 (1993) 3679.