Electrical Properties of Metal – Insulator – Metal Diode for AM-LCD Driving

[1]Jang Kwon Kim, [2] Myung Jae Lee, [3]Dong Sik Kim, [2]Kwan Soo Chung
[1]Dept. of Electronic & Telecommunication Engineering Daelim Technical College
526-7 Bisan-dong, Anyang-si, Kyungki-do, Republic of Korea
[2]Dept. of Electronics Engineering, KyungHee University
1 Sucheon-ri , Kiheung-eup, Yongin-si, Kyungki-do, Republic of Korea
[3]School of Computing & Information Systems Inha Technical College
253 Yonghyun-dong , Nam-gu. Incheon-si, Republic of Korea
Tel: [1]+82-31-467-4873,[2] +82-31-201-2958,[3]+82-32-870-2334,
E-mail:jkkim@daelim.ac.kr,lmj1@nms.kyunghee.ac.kr,blue@inhatc.ac.kr, kschung@nms.kyunghee.ac.kr

Abstract : Tantalum pentoxide (Ta_2O_5) is a candidate for use in metal-insulator-metal diode in switching devices for active-matrix liquid-crystal displays. The MIM diode with very low threshold voltage and perfect symmetry was fabricated. High quality Ta_2O_5 thin films were obtained by using an anodizing method. Rutherford backscattering spectroscopy, transmission electron microscope observations, auger electron spectroscopy, ellipsometry measurements, and electrical measurements, such as current - voltage(I-V) measurements were performed to investigate Ta_2O_5 films and their reliability and indicated that the obtained TaO_X thin films were reliable Ta_2O_5 films for the applications. Furthermore, in this paper, we discuss the effects of top-electrode metals and annealing conditions. The conduction mechanism of the leakage current and the symmetry characteristics related to the Schottky emission and Poole-Frankel effect are also discussed using the results of electrical measurements and conduction barrier theory.

1. Introduction

In recent years, there has been a remarkable progress in mobile communication industry. The usage of portable information devices such as personal digital assistants (PDAs), mobile phones and smart cards is increasing in accordance with the development of computers and mobile communication systems. The mobile communication devices require the display with high performances such as high speed, low power, and full color, etc. Especially, a switching device is absolutely necessary for moving pictures in IMT-2000. In spite of their high performance, thin-film transistor liquid-crystal displays(TFT-LCDs) have some disadvantages such as high production cost and high power consumption, and supertwisted nematic (STN) LCDs have a low quality of display for moving pictures. Therefore, currently, metal-insulator-metal (MIM) LCDs are emerging as a candidate for TFT LCDs in the fields of small size electronics due to their relatively high performance, low power consumption and low production cost [1-3]. It has many advantages, for example, low supplying power, and low cost, etc. So, it is expected to be one of the best candidates for displays of IMT-2000. In order to apply the MIM-LCD to mobile communication devices, both of higher performance and lower supplying power for display should be satisfied [4,5]. For higher performance, it is required that the MIM device has a perfect symmetrical curve of a I-V characteristic while a positive voltage and a negative voltage are applied. Also, for lower supplying power, display should be turned on at lower threshold voltage.

MIM has an oxide layer between upper and lower metal electrodes. The quality of the oxide is one of the important factors that determine the performance and supplying power of display. Conventionally, Ta_2O_5 is used as the oxide. Ta_2O_5 is fabricated by anodization, sputtering, CVD, etc. Among these methods, anodization is preferred because the anodized Ta_2O_5 has many advantages such as low cost, high breakdown voltage and low leakage current. However, the problem of the anodized Ta_2O_5 is the asymmetry of I-V characteristic curve. This asymmetry causes the image-sticking problem and degrades the performance of the display [4]. The electrical conduction of anodized Ta_2O_5 films has been investigated in order to improve the asymmetry. A TFD element with a $Cr/Ta_2O_5/Ta$- or a $Ti/Ta_2O_5/Ta$-type MIM diode was chosen and studied.

The fabricated MIM device was investigated and characterized by TEM, RBS, and electrical measurements, respectively.

2. Experiments

A simple structure with one MIM and one electrical path was designed. As a substrate, high temperature glass was used. Its size was 7 × 7 cm. An etch stopper was formed on the glass substrate to prevent the damage of the glass. As a lower electrode, Ta was coated by sputtering. Ta was patterned by photolithography and wet etching. Then, anodization was performed at room temperature in dilute ammonium tartrate aqueous solution as an electrolyte. A constant current (1 mA/cm^2) was applied to the samples until the desired voltage was reached. The thickness of the Ta_2O_5 layer was linearly related to the final anodization voltage with a proportionality constant of approximately 14.7Å/V at room temperature. Next, as a counter-electrode, a Cr or a Ti film was deposited on the Ta_2O_5/Ta array to a thickness of 200 nm by RF sputtering in Ar gas and was patterned by using a photo-engraving process(PEP). The electrical characteristics of the Ta_2O_5 films were studied as functions of the electric field and the temperature(150~400℃). An HP4145B semiconductor parameter analyzer pA meter was used to measure the current-voltage (I-V) characteristics and the breakdown voltage. The breakdown voltage was defined as the current compliance of the instrument, which was 4×10^{-2} A. The surface and the cross-section of the fabricated MIM device was observed and analyzed by optical microscope, Transmission Electron Microscope (TEM), and Rutherford Back Scattering (RBS), respectively.

3. Results & Discussions

3.1 Fabrication of the MIM device

The quality of anodized Ta_2O_5 layer is mainly influenced by current density [6]. So, multi-step anodization was attempted in this work. The method is. The first step is to increase the current density step by step. The second step is to keep the current density constant in order for steady state growth. The last step is to decrease the current density exponentially. MIM device was well fabricated without damage of substrate. Figure 1 depicts a RBS profile. The observation shows the spectrum of 2-MeV He ions backscattered from the oxide film at an 80 °tilting angle. The straight line shows the simulated results for a standard Ta_2O_5 film, and the dotted line shows the spectrum of the anodized oxide film. The measured spectrum coincided with the simulated results, and no differences between the as-deposited Ta_2O_5 film and thermally treated Ta_2O_5 films were observed in this experiment. Therefore, we conclude that the oxide films (TaO_X) obtained from the anodizing process are reliable Ta_2O_5 films.

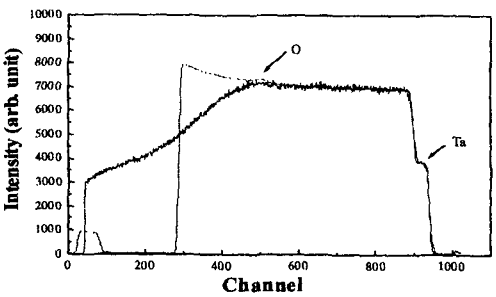
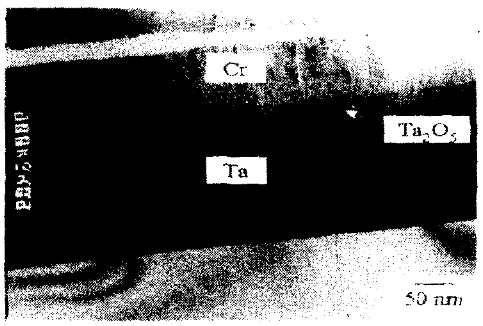


Fig. 1. RBS profile of a Ta_2O_5 film anodized on a Ta thin film deposited on a Si substrate.

For detail investigation of tantalum oxide and two electrodes, cross-section of the MIM was observed by TEM. As shown in Fig. 2, the oxide layer was uniform and clean. The thickness of the oxide was 27nm. From this result, it is known that the thickness is controlled well by the anodization method. However, void defect was found at the interface between oxide and top electrode. The reason of the defect is suspected due to mismatch between two layers caused by surface roughness of the tantalum oxide. The surface roughness causes non-uniform distribution and local concentration of current. In consequence, it accelerates breakdown of MIM device [7]. So, this mismatch defect at the interface should be improved for high performance and reliability.

Fig. 2. Cross-sectional of TEM image of Ta_2O_5.



3.2 I-V Characteristics of the MIM device

The fabricated MIM element was annealed at 150~450℃ for 2h in a vacuum. The electrode annealing seemed to a key process that affected the electrical properties since the interface states between the Ta_2O_5 and both electrodes constituted a portion of the leakage current. The reasons for increasing current density with increasing annealing temperature are thought to be reduced the barrier heights[12] of the interfaces between the Ta_2O_5 layer and the two electrodes.

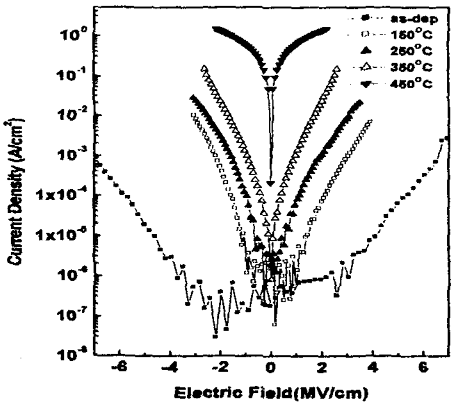


Fig. 3. I-V characteristics for an anodized Ta_2O_5 film with a 610-Å thickness for a various annealing temperatures.

The leakage current increases with increasing annealing temperature as shown in Fig. 3. In order to improve current-voltage symmetry characteristics of MIM devices, we suggest postannealing of the whole TFD element. As shown in Fig. 4, a high-performance MIM device with perfect symmetry could be achieved by using novel technologies and a TFD element with a $Ti/Ta_2O_5/Ta$ element annealed at 350℃ for 2h in a vacuum. This device exhibited an acceptable low leakage current density (below 10^{-7} A/cm^2 at 2MV/cm), a reasonable breakdown voltage (5 - 7 MV/cm) and a high dielectric constant (23 - 29).

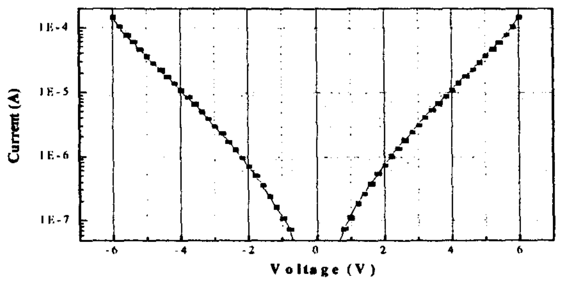


Fig. 4. I-V Characteristics of the MIM device with low threshold voltage and perfect symmetry

3. 3 Conduction Mechanisms of MIM Devices with Ta_2O_5

The leakage current in a dielectric film can be due to several conduction mechanisms, including Schottky emission [7], Poole-Frenkel emission [9,10], Fowler-Nordheim tunnelling and space-charge-limited current (SCLC) [11]. Electronic conduction in a thin Ta_2O_5 film has been interpreted in terms of electronic conduction theories. A perennial problem is the question whether the dc conduction is controlled by a Schottky emission (**SE** electrode-limited conduction) or by a Poole-Frenkel (**PF**, bulk-limited conduction) mechanism. Schottky emission is described by [7]

$$J_{SE} = A T^2 \exp\left[\frac{q\left(-\Phi_B+\sqrt{qE/4\pi\varepsilon_i}\right)}{kT}\right] \quad (1)$$

and Poole-Frenkel emission by [7]

$$J_{PE} = C E \exp\left[\frac{q\left(-\Phi_i+\sqrt{qE/\pi\varepsilon_i}\right)}{kT}\right], \quad (2)$$

where J is the current density (A/cm^2), A is the Richardson constant, which is equal to 120 A/cm^2-K^2, T denotes the absolute temperature, q is the elementary electric charge, k represents the Boltzmann constant, C is a constant, E represents the electric field, Φ_B is barrier height, Φ_i is the depth of the donor level of the oxide, and ε_i is the insulator dielectric constant of the oxide.

The interpretation of conduction mechanisms from the experimental data has been done by using the measured slope of the log(J) vs $E^{1/2}$ and log(J/E) vs $E^{1/2}$ plots. If the measured value of log(J) vs $E^{1/2}$ is linear, the conduction mechanism is considered to be a **SE** (electrode-limited)process. On the other hand, if the measured value of log(J/E) vs $E^{1/2}$ is linear, the conduction mechanism is considered to a **PF** (bulk-limited)process.

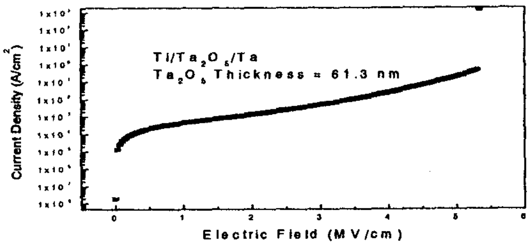


Fig. 5. I-V characteristics of a MIM capacitor with the top positively biased Ti electrode annealed at 150℃ for 2h in vacuum. The size of the MIM is 20 ㎛x20 ㎛.

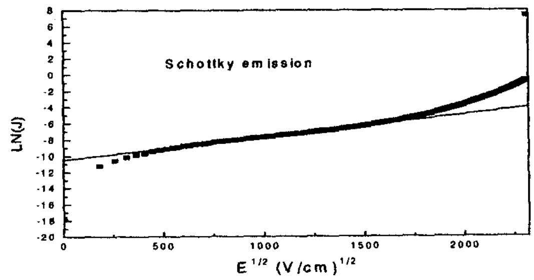


Fig. 6. Ln(J) as a function of $E^{1/2}$ of Fig. 8 for an amorphous tantalum oxide MIM diode. The straight line behavior at low electric field (< 2.2 MV/cm) indicates Schottky a emission mechanism.

Figure 5 shows the leakage current density vs applied electric field for a MIM capacitor with the top Ti electrode. Figure 6 plots the logarithmic current density as a function of the square root of the electric field [log(J) vs $E^{1/2}$]. Under a low electric field (< 2.2 MV/cm), a straight line can be obtained. The dominant conduction mechanism at low fields is, therefore, determined to be Schottky emission.

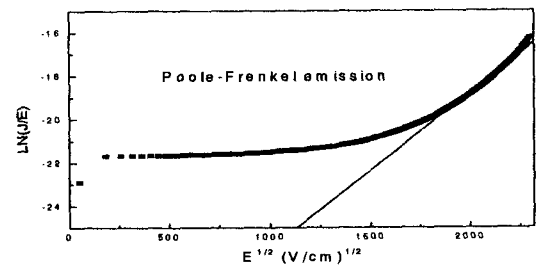
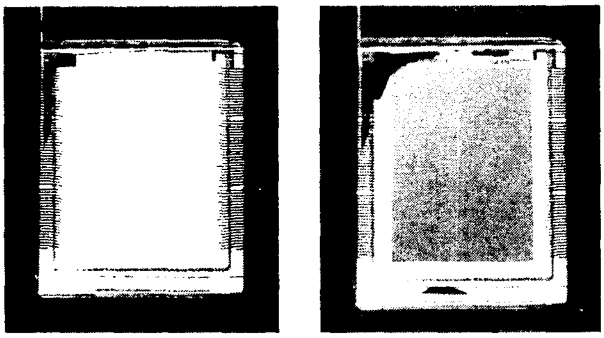


Fig. 7. Ln(J/E) as a function of $E^{1/2}$ of Fig. 8 for a tantalum-oxide MIM diode. The straght line behavior at high electric fields (2.2 - 5.2 MV/cm) indicates a Poole-Frenkel conduction mechanism.

The electrical conduction is governed by a different mechanism at higher electric fields. Figure 7 plots the logarithmic current density divided by the electric field as a function of the square root of the electric field [log(J/E) vs $E^{1/2}$]. The curve is a straight line at high electric fields (> 2.2 MV/cm^2). Therefore, the dominant conduction mechanism in this high field range is considered to be a Poole-Frenkel conduction mechanism. As shown in Fig. 8, high performance MIM-LCD was fabricated. The switching operation of the MIM-LCD was very uniform. So, in this work, we could fabricated a high performance 2"MIM-LCD using our own developed processes.



(a) On-state (b) Off-state

Fig. 8. Operation of 2-inch MIM-LCDs developed with OPTA process

4. Conclusion

In this work, we successfully fabricated Ta_2O_5 thin films by anodic oxidation and investigated the electrical and physical characteristics. Using a novel postannealing process, we developed a MIM device with reduced asymmetry and with almost perfect symmetry in the *I-V* characteristics. Taking into account our experimental results, it is evident that the characteristics of turn-on voltage, leakage current and breakdown voltage vary with the annealing temperatures and top electrode material. Also, we identified two types of conduction in the Ta_2O_5 films. Schottky emission was the dominant conduction mechanism at low electric fields below 2.2 MV/cm, and Poole-Frenkel emission was dominant at high fields above 2.2 MV/cm. It is thought that this MIM device can be applied to the high performance display for IMT-2000.

5. References

[1] T. Hirai, H. Morita, and M. Tasaka: Jpn. J. Appl. Phys., **38** (1999) 6549.

[2] H. Liu, Y. Wu, J. Yuan, K. Ma, and X. Huang: Jpn. J. Appl. Phys.**36**(1997) 7334.

[3] T. Hirai, H. Morita, and M. Tasaka: Jpn. J. Appl. Phys. **39** (2000) 657.

[4] T. Hirai et al, "Influence of Current-Voltage Characteristics on Image-Sticking of Thin-Film-Diode of Liquid-Crystal Displays", Jpn. J. Appl. Phys., Vol. 38, 1999, p. 5287.

[5] S. Zhang et al, " A Novel Self-Aligned Bidirectional MIM Diode with Transparent Junctions for AM-LCD's", IEEE Electron Device Letters, Vol. 19, No. 6, June 1998, p. 192

[6] T. Hirai et al, " Current-Voltage Characteristics of Thin-Film Diode Elements and Application of Poole-Frenkel Equation", Jpn. J. Appl. Phys., Vol. 38, 1999, p. 6549.

[7] Structural and Optical Properties of TiO_2-SiO_2 Composite Films Prepared by Aerosol-assisted Chemical-Vapor Deposition, Jong-Gul Yoon, Hun Kyoo Oh and Yong Jik Kwag, J. Korean Phys. Soc., Vol. 33, p. 699 (1998).

[8] M. G. Pitt et al, " A Reflective Active Matrix LCD Using A Two Mask Thin-Film Diode Process", SID 97 Digest, p. 473.

[9] J. Frenkel, Phys. Rev. 54, 647 (1938).

[10] Barrier-Height Effects on Lasing Characteristics of InGaAs/InGaAlAs Strained Quantum Well Lasers, Seoung-Hwan Park, J. Korean Phys. Soc., Vol. 32, p. 713 (1998).

[11] R. A. B. Devine, L. Vallier, J. L. Autran, P. Paillet, and J. L. Leray, Appl. Phys. Lett. 68, 25 (1996).

[12] Temperature Anodizing Method", Jpn. J. Appl. Phys., Vol. 30, No. 12B, 1991, p.3729

[13] L. Vaquez et al, "AFM Study of the Dielectric Breakdown in Ta_2O_5 Films", Chem. Mater., Vol. 7, 1995, p. 1680