

Study of Lanthanum incorporated HfO₂ nano-scale high-κ dielectric using Pulse Laser Deposition for metal–insulator–metal capacitor applications

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Abstract. Studies of Metal–insulator–metal (MIM) capacitors having high-κ La₂O₃/HfO₂ dielectric stacks are fabricated using Pulse Laser Deposition (PLD) is carried out. Nano-sized La₂O₃/HfO₂ dielectric stacks are deposited using PLD system under optimized pressure, substrate temperature and numbers of shots inside argon ambient chamber. The morphology of dielectric stacks is examined using AFM and the thickness of the film is examined using an ellipsometer. The elemental composition of the dielectric film was characterized using X-ray diffraction. The electrical property of the dielectric stacks was investigated employing Al-HfO₂/La₂O₃–Al-Si MIM capacitor structure. Fabricated MIM capacitors are characterized for the determination of capacitance density, dielectric constant and leakage current density for lanthanum incorporation. It can be seen that Lanthanum incorporation in HfO₂ based dielectric stacks has relatively higher capacitance, higher dielectric constant and lower leakage current which makes it one of the most promising candidates for next generation metal–insulator–metal capacitor applications.

Keywords: Metal–Insulator–Metal, Lanthanum Oxide, Hafnium Oxide, Pulse Laser Deposition.

1. Introduction

Metal–insulator–metal (MIM) capacitor is an important passive device used in silicon mixed signal integrated circuit applications for various analog and RF applications. SiO₂ and Si₃N₄ were traditionally used for fabrication of MIM structures; but off lately it has a major drawback due to its low dielectric constants (3.9 for SiO₂, 7 for Si₃N₄) [1]. With the continuous scaling down of the chip dimensions in addition to low cost per function requirements of passive device, there is an urgent need to increase the capacitance density of MIM capacitors. This requirement of higher capacitance density in MIM capacitors can be simply be achieved by reducing the high-κ dielectric thickness but has a major drawback like higher leakage current and low voltage linearity. The other method to achieve higher capacitance density in MIM capacitors is by using high dielectric constant (high-κ) materials [2]. Recently, many different high-κ [3-6] based capacitors including HfO₂ based MIM capacitors have been reported [7]. La₂O₃ seems to be a promising alternative high-κ material with the merits of high energy band gap as well as good thermal stability with Si [8,9]. Recently, different deposition technique is being used to deposit gate dielectric and gate dielectric stacks so as to identify the best deposition technique for best electrical outputs [10-13]. In this paper, we present results of HfO₂ dielectric film, when incorporated with La as a MIM structure on the top of Al/Si substrate using PLD machine for the first time. The surface study and film thickness of the as-deposited dielectric films/stacks are studied using Atomic Force Microscope (AFM) and ellipsometry respectively. The chemical composition and physical properties of the post-deposited films are studied using X-ray diffraction (XRD).

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The electrical properties mainly the capacitance density, dielectric constant and leakage current of the dielectric/stacks as MIM capacitors are extracted and studied using the high frequency (1 MHz) C–V curve.

2. Experimental Details

HfO₂ with high purity (99.9% purity) supplied by M/s Semiconductor technology and La₂O₃ from RE acton, Alfa Aesar, Johnson Mathey Company with 99.9% purity in the form of pellets are used as targets to deposit the thin dielectric stacks using PLD machine as shown in Fig. 1. PLD system manufactured by CONTINUUM Surelite III-10 is used to deposit the thin film dielectric stacks to fabricate MIM capacitors. The PLD system used for dielectric deposition has an Nd-Yag/ KrF Laser having wavelength of 1064/ 248 nm with laser energy density of ~ 3.0 J/cm², pulse repetition rate of 10 Hz and pulse width of 10 ns to deposit thin dielectric films from the targets of 25 mm diameter. P-type silicon substrate on which aluminum layer is pre-deposited is used to deposit La₂O₃/HfO₂ dielectric stacks. The p-type silicon wafers were cleaned using the standard pirana cleaning procedure in order to remove any kind of organic and inorganic contaminations. The wafers were etched in dilute HF (1:20), rinsed in DI water and dried in dry nitrogen atmosphere. A 200 nm thick Al metal film was deposited using dc sputtering in Ar ambient on Si structures to serve as the bottom electrode for MIM capacitor before loading in the vacuum chamber. Laser beam focus through the quartz lenses and strike the target at 45° resulting in plasma plume of 1-inch diameter. The distance between the target and metalized substrate is around 4 cm. The background pressure of the vacuum chamber was maintained at 10⁻⁶ torr and the PLD system was operated at an optimized temperature and in high purity nitrogen gas. The gas pressure was maintained at 100 m torr. 100 shots are used for deposition of each target. The top electrodes (Al dots) on as-deposited films were fabricated by thermal evaporator using the shadow mask technique having diameter of around 200 microns (Area = 126.50 μm²). The physical thickness of the high-κ gate stacks dielectric is measured using Laser Ellipsometer (Sentech Instruments Laser-Pro) and the microstructure was examined by VEECO-CPII Atomic Force Microscope. The structural properties of deposited gate stacks is obtained by means of XRD which is measured using Rigaku, Rotaflex rotating anode XRD instrument and Room-temperature I-V characteristics of MIM structures are measured by KEITHLEY 2400 unit.

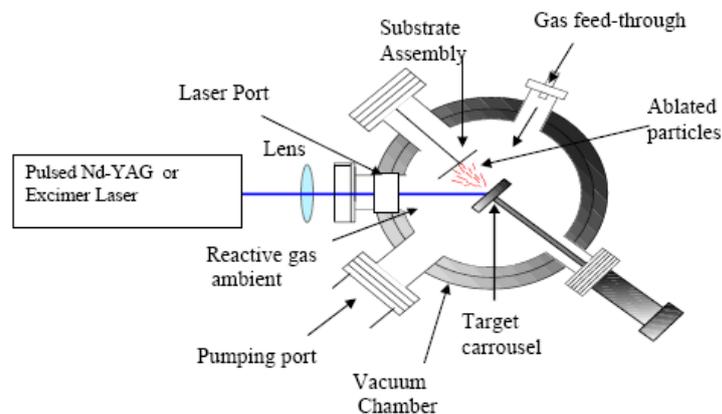


Fig.1 Schematic of Pulse Laser Deposition

3. Results

Fig.2 shows the AFM image with a scan area of 1 μm x 1 μm for the deposited HfO₂ dielectric on the top of Al-silicon substrates using 450 PLD shots. The AFM image shows the formation of nanostructures. The size of the nanostructures is found to lie around 10-20 nanometers. The maximum height of the nanostructures is found to be above 80 nanometers. The rms roughness and average roughness of nanostructures is found to be 22 nanometers and 19 nanometers respectively. The physical thickness of the high-κ gate stacks dielectric is measured to be around 200 nm; measured using Laser Ellipsometer.

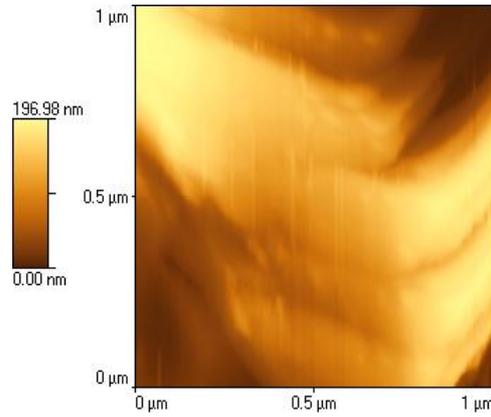


Fig.2 AFM of HfO₂ thin film MIM capacitors deposited using PLD shots

Figure 3 shows the XRD spectra of La₂O₃/HfO₂ gate stacks deposited by PLD. It shows the peaks corresponding to HfO₂, La₂HfO₇ and La₂O₃. This presence of La₂HfO₇ helps us to confirm that there is incorporation of La in hafnium based gate dielectric over the Al/Si wafer.

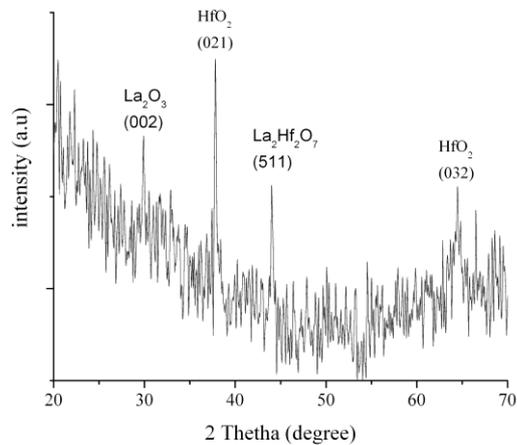


Fig.3 XRD of La₂O₃/HfO₂ thin film MIM capacitors deposited using PLD shots

Fig.4 shows the AFM image with a scan area of 1 μm x 1 μm for the deposited La₂O₃/HfO₂ dielectric on the top of Al-silicon substrates. The maximum height of the nanostructures is found to be ~ 57 nanometers. The rms roughness and average roughness of nanostructures is found to be 10 nanometers and 16 nanometers respectively.

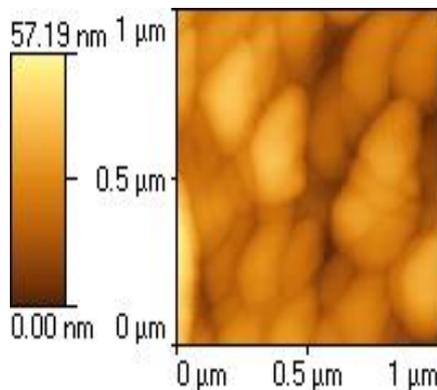


Fig.4 AFM of La₂O₃/HfO₂ thin film MIM capacitors deposited using PLD shots

The room-temperature I-V characteristics of lanthanum incorporated hafnium oxide gate stacks MIM device deposited using PLD under pressure of 10 mTorr for 100 PLD shots each is shown in Figure 5. I-V characteristics is measured both in accumulation and inversion region. It is observed that current increases with voltage for both accumulation and inversion regions. The gate current for forward gate and reverse gate voltage is similar.

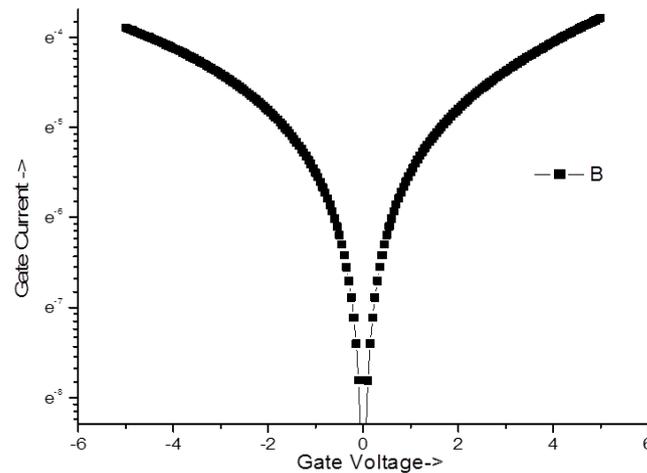


Fig.5 I-V Capacitors of $\text{La}_2\text{O}_3/\text{HfO}_2$ based MIM capacitors deposited using PLD shots

4. Conclusion

Preliminary results show a successful deposition of Lanthanum incorporated HfO_2 dielectric stacks using PLD shots under optimized conditions for fabrication of MIM capacitors. Initial morphological and electrical results of $\text{La}_2\text{O}_3/\text{HfO}_2$ dielectric stacks deposited using PLD shots are shown in this article. The AFM image shows the formation of nanostructures of HfO_2 and Lanthanum dielectric stacks. The RMS roughness and average roughness of the dielectric stacks was of the order of few nanometers. We will show the improvements in the electrical properties with incorporation of lanthanum in hafnium based dielectric stacks and study its relationship with the morphological changes in $\text{La}_2\text{O}_3/\text{HfO}_2$ dielectric stacks as a MIM capacitor using the PLD deposition technique at the conference presentation site.

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6. References

- [1] P. Zurcher, P. Alluri, P. Chu, P. Duvallet, C. Happ, R. Henderson, J. Mendonca, M. Kim, M. Petras, M. Raymond, T. Rimmel, D. Roberts, B. Steimle, J. Stipanuk, S. Straub, T. Sparks, M. Tarabbia, H. Thibieroz, M. Miller, *Int. Electron Devices Meeting Tech. Dig* 2000, : 153.
- [2] S.B. Chen, J.H. Chou, A. Chin, J.C. Hsieh, J. Liu, *IEEE Electron Device Lett.* 2002, 23: 185.
- [3] K.C. Chiang, J.W. Lin, H.C. Pan, C.N. Hsiao, W.J. Chen, H.L. Kao, I.J. Hsieh, A. Chin, *J. Electrochem. Soc.* 2007, 154: H214.
- [4] C.H. Cheng, S.H. Lin, K.Y. Jhou, W.J. Chen, C.P. Chou, F.S. Yeh, J. Hu, M. Hwang, T. Arikado, S.P. McAlister, Albert Chin, *IEEE Electron Devices Lett.* 2008, 29: 845.
- [5] S.J. Kim, B.J. Cho, M.F. Li, S.J. Ding, M.B. Yd, C. Zhu, A. Chin, D.L. Kwong, *VLSI Tech. Dig.*, 2000), 218.
- [6] M.Y. Yang, C.H. Huang, A. Chin, C. Zhu, M.F. Li, D.L. Kwong, *IEEE Electron Devices Lett.*, 2003, 24: 306.

- [7] H. Hu, C. Zhu, Y.F. Lu, M.F. Li, B.J. Cho, W.K. Choi, *IEEE Electron Devices Lett.* 2002, 23: 514.
- [8] H. Wong, H. Iwai, On the scaling issues and high-k replacement of ultrathin gate dielectrics for nanoscale MOS transistors. *Microelectron Eng* (2006); 83: 1867.
- [9] H. Wong, H. Iwai. The road to miniaturization. *Phys World*, 2005, 18(9): pp. 40.
- [10] H.Fujisawa, A. Srivastava, K. Kakushima, P.Ahmed, K. Tsutsui, N.Sugii, T. Hattori, C. K. Sarkar and H.Iwai, Electrical Characterization of W/HfO₂ MOSFETs with La₂O₃ Incorporation, *ECS Trans.*, 2009, 18 (1):39.
- [11] A.Srivastava, R. K. Nahar, C. K. Sarkar, Y. Malhotra, Study of hafnium oxide thin film deposited using Dense Plasma Focus machine as a gate dielectric for a MOS device, *Microelectronics Reliability*,2011, 51 (4):751-755.
- [12] D. Zade, S. Sato, K. Kakushima, A. Srivastava, , P. Ahmet, K. Tsutsui, A. Nishiyama, N. Sugii, K. Natori, T. Hattori, C. K. Sarkar, and H. Iwai, Effects of La₂O₃ incorporation in HfO₂ gated nMOSFETs on low-frequency noise, *Microelectronics Reliability*,2011, 51(4):746-750.
- [13] A.Srivastava, C. K. Sarkar, Dielectric property of CaCu₃Ti₄O₁₂ thin film grown on Nb doped SrTiO₃ (100) single crystal, *Appl. Phys. A: Materials Science & Processing*, 2009, 97 (2):409-416.