STRUCTURAL AND ELECTRICAL PROPERTIES OF TANTALUM PENTAOXIDE (Ta_2O_5) THIN FILMS – A REVIEW

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Down scaling of complementary metal oxide semiconductor transistors has put limitations on silicon dioxide to be used as an effective dielectric. It is necessary to replace the SiO_2 with a physically thicker layer of oxides of high dielectric constant. Thus high k dielectrics are used to suppress the existing challenges for CMOS scaling. Many new oxides are being evaluated as gate dielectrics such as Ta_2O_5 , HfO_2 , ZrO_2 , La_2O_3 , HfO_2 , TiO_2 , Al_2O_3 , Y_2O_3 etc but it was soon found that these oxides in many respects have inferior electronic properties to SiO_2 . But the choice alone of suitable metal oxide with high dielectric constant is not sufficient to overcome the scaling challenges. The various deposition techniques and the conditions under which the thin films are deposited plays important role in deciding the structural and electrical properties of the deposited films. This paper discusses in brief the various deposition conditions which are employed to improve the structural and electrical properties of the deposited films.

Keywords: CMOS, DC sputtering Oxygen flow rate.

1. Introduction

An effective approach to enhance transistor performance in complementary metal-oxide semiconductor (C-MOS) technologies is scaling of silicon dioxide dielectrics as predicted by Moore's law. Thus, in the past few decades, reduction in the thickness of silicon dioxide gate dielectrics has enabled increased numbers of transistors per chip with enhanced circuit functionality and performance at low costs (Fig.1). But the miniaturization of integrated devices brings serious challenges to the continued use of current materials, the Capacitor used in traditional microelectronic circuits composed of $\text{Si}/\text{SiO}_2/\text{metal}$ will not be able to function due to the physical Limits of SiO_2 dielectric. At the nanometer dimensions, the SiO_2 dielectric constant is not large enough to prevent leakage current, leading to the unwanted discharge of the capacitor.

New higher (k) materials are under consideration and have been studied extensively, and many potential materials such as Ta_2O_5 , HfO_2 , ZrO_2 and their silicates have shown promise as a replacement for SiO_2 . But the alone choice of high k material will not be the solution to the existing problem. Deposition technique of thin films along with other

experimental conditions must be taken into consideration to attain good quality thin films to meet the requirements of CMOS scaling. For eg. Tantalum pentaoxide has proved to be a potential replacement for traditional dielectric silicon dioxide, but the as deposited film suffers from many technical shortcomings which needs to be rectified before considering it as a potential substitute.

2. Annealing of Ta₂O₅ Thin Films under UV-O₃ Atmosphere with Ultraviolet Light Radiation

Annealing of Ta₂O₅ thin films under UV-O₃ atmosphere with ultraviolet light radiation [Dail Eom et al 2004] at 450°C has been found to be a very efficient way to improve the crystallization of the film during post annealing and to reduce the oxygen vacancy concentration. The reason for the enhanced crystallization behavior of the UV-O₃ treated films was found from the oxygen enrichment of the tantalum oxide films as a result of the UV-O₃ treatment, due to high oxidation potential of O₃ which was further assisted by UV illumination at relatively low temperature treatment (450°C) [8]. The tantalum oxide films without the UV-O₃ treatment mostly exhibited the Poole-Frenkel conduction behavior with the electron trap level of 0.62 eV from the conduction band edge. The partially UV-O₃ treated films exhibited a direct tunneling behavior in a relatively low voltage region by the tunneling through the thin (around 3.8nm) UV-O₃ treated surface layer [8]. Also the UV-O₃ treatment was found to be an efficient method to reduce the leakage current through tantalum oxide films. But the P-F conduction mechanism was still found to work with a greatly reduced leakage current density due to the decreased trap density as a result of UV-O₃ treatment.

The sputter deposited thin films tend to show film porosity, which effects the electrical and the optical properties [Eva FRANKLE et. al.] As the sample ageing due to moisture incorporation followed by chemical degradation may decrease the electrical, and increase light scattering at rough interfaces. It has been reported that refractive index is a function of the deposition temperature [9-11] and total gas pressure [10,12] during sample growth. As temperature and total gas pressure affect the thin film porosity, the refractive index of tantalum oxide films also increase by film densification, and hence an effective refractive index of tantalum oxide films results from growth conditions, and may range from $n=2.06$ (by evaporation method) to $n=2.25$ (by ion plating method) at wavelength of 550nm. The difference in the values of refractive index are mostly due to different thin film porosity [13,14] which is known to be higher for films grown by evaporation than by ion plating. It has been reported that the mixtures of substoichiometric and stoichiometric tantalum oxide causes lower refractive index values in tantalum oxide thin films [14,17].

3. Aluminium Addition

It is also stated that the dielectric and insulating properties of Ta₂O₅ gets significantly modified by addition of aluminium [Chandra S. Desu]. It has been found that Al addition has decreased the leakage currents and improved thermal and bias stability characteristics of Ta₂O₅ capacitors. The leakage current in crystalline pure Ta₂O₅ thin films were found to be 4.5×10^{-7} A/cm² in a 1MV/CM DC field which decreased to a value of 3.4×10^{-8} A/cm² for 10% Al modified Ta₂O₅ thin films. A typical dielectric constant of 42.5 was obtained for 10% Al modified Ta₂O₅ thin films [15]. This is significantly higher as compared to the commonly reported dielectric constant of 25 to 35 for tantalum oxide

thin films. Also incorporation of Hf with Ta₂O₅ reduces the fixed charge density as well as leakage current [Jagadeesh et al; 2008]. Addition of Zr with Ta₂O₅ increases the dielectric strength.

4. Negative Bias to Si Substrate

The tantalum oxide thin crystalline films were also obtained at low temperature by applying a negative bias to Si substrate, [A.P.Haung et al.] it was found that at 620°C the thin films as prepared were amorphous without the bias but the crystallinity was found to increase with the negative bias given to the substrate (i.e.-100V)[16]. Also it is reported that on increasing the negative bias to -200V, partially crystallized films could be attained at temperature as low as 400°C, and thus the problem of formation of interfacial layer between silicon substrate and Ta₂O₅ thin films at high temperature can be overcome. The crystallinity enhancement could be attributed to the accelerated interaction of positive ions in the plasma with the growing surface, as the bias induces the positive ions with high energy, the diffusion of deposited particles and the relaxation of the growing surface are probably enhanced by the collision of the accelerated positive ions in the sheath of plasma. Thus the thin films with high crystallization could be attained. Also work has been done to study the stability properties of Ta₂O₅ thin films [H.Zorc et al.] Deposition of tantalum oxide films were carried out with and without ion assist, and it was found that Ta₂O₅ thin films deposited with ion assist are more stable than those deposited without ion assist.

5. Oxygen Flow Rate

We have worked to check the effect of oxygen flow rate on the crystalline behavior of the tantalum thin film deposited. For this tantalum oxide films were deposited by reactive sputtering of a tantalum (Ta) target, in mixed argon (Ar) and oxygen atmosphere. The flow rate of Ar was maintained constant at 50 sccm while flow rate of oxygen was varied at kept at 5, 7 sccm, 10 sccm and 15 sccm for different composition of the film. The total pressure during the deposition in the chamber was kept at 100 mtorr. The sputtering power was kept 100 watt. The X-RD pattern is shown in the fig 2. Two peaks occurred corresponding to (001) (201) plane Ta₂O₅ indicating that amorphous thin films could be crystallized by varying the oxygen flow. Deposition rate of thin films is found to decrease from 9.2 nm/min to 3.3 nm/min with increase in oxygen flow rate from 5% to 15%. The refractive index values are also found to vary with oxygen flow rate. Average roughness and root square roughness of tantalum oxide thin films are also found to increase with increase in oxygen flow rate, which may be due to the fact that presence of oxygen act as impurities in the film and it reduces the movement of tantalum on the surface and hence the roughness increase increases.

Fig 2 : X-RD Pattern

Grain size is also found to decrease with increase in oxygen flow rate. Dielectric constant is also found to increase up to 38 from the usual value of 29 with oxygen flow rate. The transmittance of the thin films is found to be almost independent of oxygen flow rate. Thus a number of deposition conditions have been successfully employed to improve the structural and electrical properties of tantalum oxide thin films.

6. Conclusion

We have discussed the various issues that needs to be considered while replacing silicon dioxide with high K dielectric to meet the requirements of the submicron devices. High K dielectric gate oxide faces several challenges in MOS devices. The major concerns are surface quality, structural defects, mobility degradation, interface fixed charge and dopant depletion in the poly Silicon gate electrode. The main considerations for these defects are different deposition technique and the different condition under which films may be deposited to attain better quality of deposited films. It has been reviewed that electrical and structural properties of tantalum oxide thin films can be improved by

1. By annealing under O_3 atmosphere with ultraviolet light radiation.
2. By applying a negative bias to the substrate crystalline nature of thin films can be obtained at low substrate temperature.
3. By introducing deuterium oxide (D_2O) as sputtering gas.
4. By varying the oxygen flow rate.

References

1. Q.Fang, J-YZhang, Z.M. Wang, J. X. Wu, B. J. O. Sullivan, P.K. Hurley, T.L. Leedham, H. Davies, M.A. Audier, C. Jimenez, J.P. Senateur, and I.W.Boyd, Interface of tantalum oxide films on silicon by UV annealing at low temperature, Thin solid films 428(2003).

2. K. Shimizu, M.Katayama , H.Funaki E.Arai, M.Nakata, Y.Ohji, and R.Imura,Stiochiometry measurement and electric characteristics of thin films Ta₂O₅ insulator for ultra large scale integration, J. Applied Phys. 74,375 (1993).
3. P.C.Joshi and M.W. Cole, J. Applied Phys.86, 871 (1999).
4. S.Ezhilvalvan and T.Y. Tseng, J.Am. Ceram. Soc. 82, 600 (1999).
5. B.K.Moon,C.Isobe, and J.Aoyama, J.Applied Phys. Lett.68,1731 (1999).
6. Z.W.Fu, L.Y.Chen, and Q.Z.Qin, Thin Solid Films 340, 164 (1999).
7. C.Chaneliere, S.Four, J.L.Autran, R.A.B.Devine, and N.P. Sandler, J.Applied Phys. 83,4823 (1998).
8. Dail Eom, In Sang Jeon, Sang Yong NO, Cheol Seong Hwang, and Hyeong Joon Kim Changes in structures and electrical conduction mechanisms of chemical vapour deposited tantalum oxide films by annealing under O₃ atmosphere with ultraviolet light radiation, School of material science and Engineering, and inter-university semiconductor research center, Seoul 151-742, Korea.
9. S.O.Kim,J.s.Byun ,and H.J.Kim, ThinSolid Films 206,102 (1991).
10. J.Y.Zhang, B.Lim, and I.W.Boyd, Thin Solid Films 336,340(1998).
11. K.kukli,J.Aarik,A.Aidla,O.Kohan,T.Uustare, and V.sammelese Ig,,Thin Solid Films 260, 135 (1995).
12. W,B.Westwood, R.J. Boynton, and S.J.Ingre, J. Vac .Sci. Technol. 11, 381 (1974).
13. M.Cevro and g.Carter, Opt. Eng. 34, 603(1995).
14. K.Gurtler, K.Bange, W.Wagner, F.Rauch, and H.Hantsche, Thin Solid Films 175, 185 (1989).
15. Chndra S. Desu, Chemically modified tantalum oxide dielectrics for high density dynamic random access memory applications, Materials science and engineering.
16. A.P.Haung,S.L.Xu, M.K.Zhu, B.Wang, and H.Yan,T.Liu,Crystallization control of sputtered tantalum oxide thin films by substrate bias, Applied Phys. Letters Vol.83, No.16 (2003)
17. Eva Franke, C.L.Trimble, M.J.De Vries and J.A.Woollam, M.Schubert, F.Frost, Dielectric function of amorphous tantalum oxide from the far infrared to the deep ultraviolet spectral region measured by spectroscopic ellipsometry, J. Applied Phys. Vol.88,(2000).