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Improved Transconductance and Gate Insulator Integrity of MISFETs with Si_3N_4 Gate Dielectric Fabricated by Microwave-Excited High-Density Plasma at 400° C

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Abstract

A low-resistivity metal gate Metal- Nitride-Semiconductor MNSFETs technology, exhibiting an excellent transconductance and high gate insulator integrity is reported. The gate stack consists of directly grown Silicon Nitride (Si_3N_4) film using microwave-excited (2.45GHz) high-density ($<10^{12}cm^{-3}$) $Ar/N_2/H_2$ or Ar/NH_3 plasma and Tantalum Nitride/*bcc*-phase Tantalum ($\sim 15\mu\Omega cm$)/Tantalum Nitride, [TaNx/(*bcc*-Ta)/TaNx] stacked metal gate (<1.0ohm/sq).

Introduction

The scaling down of MOSFETs in ULSI Technology dictate a reduction in the gate Equivalent Oxide Thickness (EOT) down to the scaling limit, resulting an increase of the leakage current, due to direct tunneling, for Tox<3nm. Accordingly an effort is made to replace SiO_2 gates by higher dielectric-constant films, such as Si_3N_4 [1][2], ZrO_2 [3] and HfO_2 [4]. Another problem regards the undesirable increase in EOT, due to the influence of the polysilicon gate depletion layer capacitance. Accordingly, in order to avoid this problem, a metal gate is proposed as a solution.

We have already reported the attractiveness of Si_3N_4 as a high-K gate insulator, grown by using microwave-exited high-density plasma at 400°C [2], and of TaNx/(*bcc*-Ta)/TaNx stack as a metal gate electrode, due to its low resistivity [7]. Accordingly, they are used in this work. As a result, an excellent transconductance of Si_3N_4-MNSFETs as well as high gate insulator integrity, of TaNx gate MNS capacitors are reported.

Experimental

TaNx MNS capacitors and TaNx/(*bcc*-Ta)/TaNx stacked metal gate FDSOI-MNSFETs were fabricated (Fig.2). The Capacitors were fabricated on Cz phosphorus doped 0.8-1.2 $\Omega\cdot$cm, (100) silicon wafers and the SOI-MNSFETs were fabricated on SOI wafers (SOI/BOX=48nm/200nm). Si_3N_4 films were grown as the gate insulator in an $Ar/N_2/H_2$ (for FETs) or Ar/NH_3 (for capacitors) plasma system (Fig.1), at pressure ratios of 93/5/2 or 96/4, respectively, at 400°C. The applied microwave power density and frequency, were $5W/cm^2$ and 2.45GHz, respectively. The three layers of the stacked TaNx/(bcc-Ta)/TaNx (=15nm/160nm/15nm) structure, were then successively deposited as a gate metal, by RF (40.68MHz, 80W) sputtering, at room temperature. S/D of FDSOI-MNSFETs was formed by ion-implantation($^{75}As^+$:15keV-1.5 $\times$ $10^{15}cm^{-2}$) and post implantation annealing at 450°C for 5hours to activate the implanted dopants [8].

Results and Discussions

Fig.3 shows C-V characteristics of TaNx/(*bcc*-Ta)/TaNx metal gate MNS capacitor. Flat band voltage shift is below 4mV. Typical Id-Vg characteristics of the MNSFET are shown in Fig.4. In Fig.5 a comparison of the transconductances(g_m) of a MNSFET and a MOSFET both with stacked TaNx/(*bcc*-Ta)/TaNx metal gates, is shown. The transconductance of nMNSFET is higher than that of nMOSFET in the high Eox range. Similar result was obtained in JVD Si_3N_4 MNSFETs [9]. Fig.6 shows the combined reflected X-Ray intensity from the Si_3N_4 surface and Si_3N_4/Si interface as well as from the SiO_2 surface and SiO_2/Si interface, as a function of the incident X-Ray angle, measured by Grazing Incident X-Ray Reflectivity (GIXR)[10]. This measurement yield the interface roughness as summarized in Table I, showing that the interface roughness of the Si_3N_4/Si is smaller than that of SiO_2/Si. TEM cross section view of TaNx/Si_3N_4/Si and TaNx/SiO_2/Si structures are shown in Fig.7, which confirm that Si_3N_4/Si exhibit smoother interface. The findings of Table I and Fig.7 can explain the higher transconductance of MNSFET than that of MOSFET (Fig.5) by the smaller interface roughness [11]. Fig.8 and 9 show the charge to breakdown and the time to breakdown characteristics, respectively, for three Vg values, of TaNx gate MNS capacitors, which exhibit high integrity thin (2.44nm) S_3N_4 gate insulator. Fig.10 was obtained from the 50% failure rate values of Fig.9. The 10 years lifetime was determined by extrapolation at Vg=2.55V for EOT=2.44nm Si_3N_4 films [12].

Conclusion

Metal-Nitride-Semiconductor MNSFETs technology is presented, exhibiting excellent transconductance and high gate-insulator integrity. The higher transconductance of the MNSFET with respect to that of MOSFET can be explained by the lower interface roughness.

Acknowledgements

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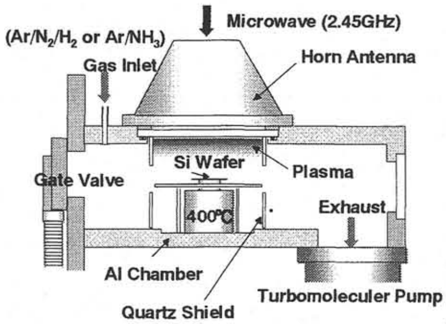


Fig.1 Microwave-excited high-density plasma system. Silicon nitride gate insulator is grown at 400℃.

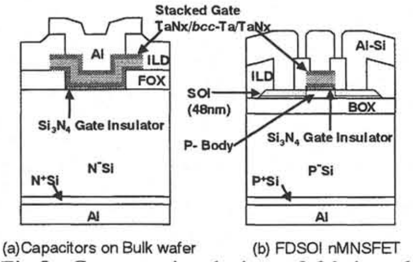


Fig.2 Cross sectional view of fabricated (a)capacitors and (b)FD-SOI MNSFETs, both devices contain TaNx/(*bcc*-Ta)/TaNx stacked a metal gate. The top TaNx is introduced as a protective layer from oxidizing ambient.

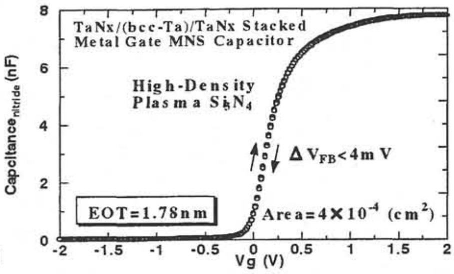


Fig.3 C-V characteristics of TaNx/(*bcc*-Ta)/TaNx stacked metal gate MNS capacitor.

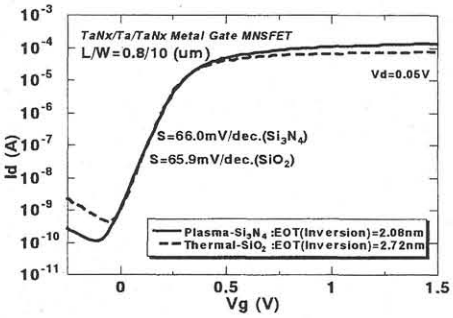


Fig.4 Id-Vg characteristics of TaNx/(bcc-Ta)/TaNx stacked metal gate FD-SOI nMNSFETs and nMOSFETs.

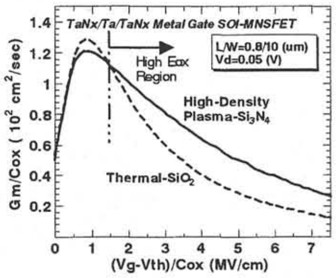


Fig.5 Comparison of trans-conductances (Vd=0.05V) of TaNx/(bcc-Ta)/TaNx stacked gate MNSFET and MOSFET.

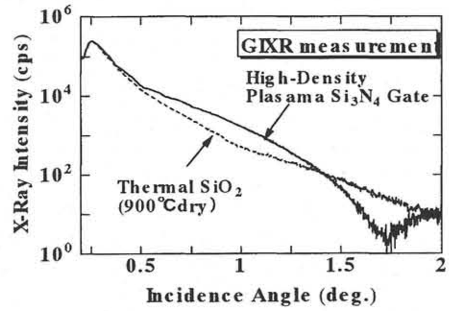
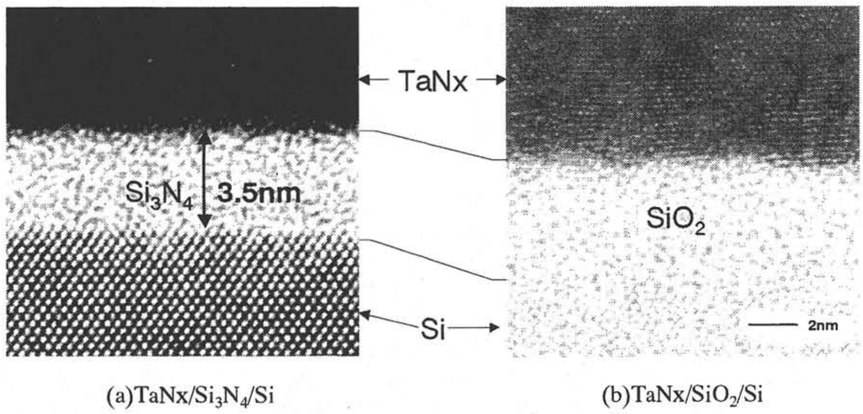


Fig.6 Combined X-Ray Intensity reflected from the surfaces of the respective insulating films and from their interfaces with the Si substrate.

Table I Interface roughness of the gate insulator/Si interface.

Gate Insulator/Si Interface	Interface Roughness
Si_3N_4/Si	Below Detection Limit (<0.1nm)
SiO_2/Si	0.29nm



(a)TaNx/Si_3N_4/Si (b)TaNx/SiO_2/Si

Fig.7 TEM cross section view of (a)TaNx/Si3N4/Si and (b)TaNx/SiO2/Si

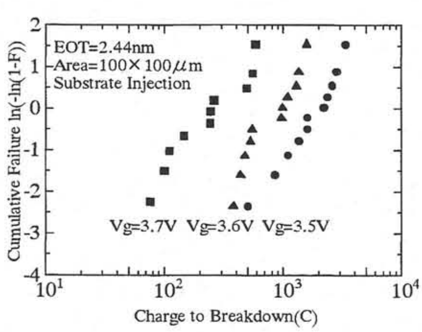


Fig.8 Charge to breakdown characterisics(Qbd) of PVD-TaNx gate MNS capacitors, for three Vg values.

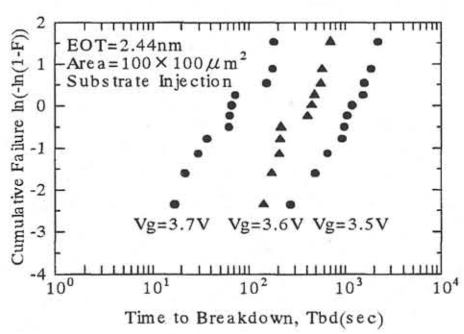


Fig.9 Time to breakdown characterisics (Tbd) of PVD-TaNx gate MNS capacitors, for three Vg values.

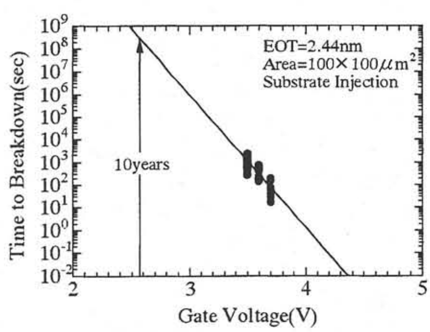


Fig.10 Lifetime extrapolation of a Si_3N_4 MIS capacitor, indicaing 10 years lifetime for Vg=2.55V.