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Improved Transconductance and Gate Insulator Integrity of MISFETs with $\text{Si}_3\text{N}_4$ 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 ($\text{Si}_3\text{N}_4$) film using microwave-excited (2.45GHz) high-density ($<10^{13}$ cm$^{-3}$) Ar/N$_2$/H$_2$ or Ar/NH$_3$ plasma and Tantalum Nitride/bcc-phase Tantalum ($\sim$15µm)/Tantalum Nitride, [TaNx/(bcc-Ta)/TaNx] stacked metal gate ($<1.0$ohm/sq).

Introduction

The scaling down of MOSFETs in ULSI Technology dictates 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$_3$N$_4$ [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$_3$N$_4$ as a high-K gate insulator, grown by using microwave-excited 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$_3$N$_4$-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 Ω·cm, (100) silicon wafers and the SOI-MNSFETs were fabricated on SOI wafers (SOI/BOX=45nm/200nm). Si$_3$N$_4$ 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 95/5 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($^{29}$As:1.5keV-1.5 × 10$^{15}$cm$^{-2}$) and post implantation annealing at 450°C for Shoures 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$_3$N$_4$ MNSFETs [9]. Fig.6 shows the combined reflected X-Ray intensity from the Si$_3$N$_4$ surface and Si$_3$N$_4$/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 1 , showing that the interface roughness of the Si$_3$N$_4$/Si is smaller than that of SiO$_2$/Si. TEM cross section view of TaNx/Si$_3$N$_4$/Si and TaNx/SiO$_2$/Si structures are shown in Fig.7, which confirm that Si$_3$N$_4$/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) Si$_3$N$_4$ 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$_3$N$_4$ 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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References

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

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

<table>
<thead>
<tr>
<th>Gate Insulator/Si</th>
<th>Interface Roughness</th>
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<tbody>
<tr>
<td>Si3N4/Si</td>
<td>Below Detection Limit (&lt;0.1nm)</td>
</tr>
<tr>
<td>SiO2/Si</td>
<td>0.29nm</td>
</tr>
</tbody>
</table>

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

Fig. 5 Comparison of transconductances (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.

(a)TaNx/Si3N4/Si  
(b)TaNx/SiO2/Si

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

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

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

Fig. 10 Lifetime extrapolation of a Si3N4 MIS capacitor, indicating 10 years lifetime for Vg=2.55V.