Nitrogen dilution effects on structural and electrical properties of hot-wire-deposited a-SiN:H films for deep-sub-micron CMOS technologies

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Abstract

Hot-wire chemical vapor-deposited silicon nitride is a potential dielectric material compared to glow-discharge-deposited material due to its lower hydrogen content. In several earlier publications we have demonstrated these aspects of the HWCVD nitride. However, to replace SiO2 with a-SiN:H as the gate dielectric, this material needs further improvement. In this paper we report the results of our efforts to achieve this through nitrogen dilution of the SiH4 + NH3 gas mixture used for deposition. To understand the electrical behavior of these nitride films, we characterized the films by high-frequency capacitance–voltage (HFCV) and DC J–E measurements. We attempted to evolve a correlation between the breakdown strength, as determined from the J–E curves, and aspects such as the bond density, etching rate, deposition rate and refractive index. From these correlations, we infer that nitrogen dilution of the source gas mixture has a beneficial effect on the physical and electrical properties of the hot-wire a-SiN:H films. For the highest dilution, we obtained a breakdown voltage of 12 MV cm⁻¹.

Keywords: Metal nitride semiconductor (MNS) devices; Silicon nitride; Nitrogen dilution; Electrical properties

1. Introduction

To continue scaling in metal oxide semiconductor (MOS) technology, the anticipated high gate leakage current in the thermal oxide needs to be suppressed [1]. Hence, it is necessary to use alternate gate dielectrics with higher dielectric constant in order to provide a physically thicker film for the required electrical oxide thickness (EOT) [2,3]. Silicon nitride, among other high-k dielectrics, is at the forefront of research, as it has a dielectric constant twice that of silicon dioxide [4,5]. It also offers a very high diffusion barrier for impurities, such as boron and sodium, and acts as a good passivating layer.

We have succeeded in developing ultra-thin ~4-nm (<2 nm of EOT) silicon nitride by hot-wire chemical vapor deposition (HWCVD) as a gate dielectric for metal nitride semiconductor (MNS) capacitors [6]. There have also been some reports from other workers on such a-SiN:H films by HWCVD [7]. In this paper we report the effect of nitrogen (N2) dilution of the silane gas on the various properties of the dielectric thin films. We varied the N2 flow from 10 to 50 sccm and monitored the variation in dielectric reliability and leakage current density. The detailed electrical characterization reveals that N2 dilution results in high breakdown strength and reduced trap generation in the dielectric thin films.

2. Experimental details

The a-SiN:H films were deposited by HWCVD using SiH4 (Matheson, USA) and NH3 (99.999%) on p-type crystalline silicon (⟨100⟩ orientation, 0.8–1.2 Ω cm resistivity) and Corning 7059 glass substrates. The silicon wafers were chemically cleaned with a standard Radio Corporation of America (RCA) cleaning procedure. The process parameters employed during deposition of a-SiN:H are shown in Table 1.

The thickness of the films was measured using two different techniques. A surface profilometer (Dektak II) was used to measure the thickness of thicker films (> 1000 Å), while the thickness of the ultra-thin films (< 4 nm) was determined from C–V data obtained on MNS capacitor structures. The infrared (IR) absorption spectra...
Table 1
Process parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gases used</td>
<td>SiH₄, NH₃</td>
</tr>
<tr>
<td>(NH₃/SiH₄) flow rate ratio</td>
<td>20</td>
</tr>
<tr>
<td>Nitrogen flow rate ratio</td>
<td>10–50 sccm</td>
</tr>
<tr>
<td>Substrate temperature (Tₛ)</td>
<td>250 °C</td>
</tr>
<tr>
<td>Filament temperature (Tₖ)</td>
<td>1800 °C</td>
</tr>
<tr>
<td>Total gas pressure</td>
<td>30–250 mTorr</td>
</tr>
<tr>
<td>Deposition time</td>
<td>40 s</td>
</tr>
<tr>
<td>Distance between filament and substrate</td>
<td>5 cm</td>
</tr>
</tbody>
</table>

of the films deposited on silicon substrates were recorded on a Nicolet FTIR spectrometer in the range 400–4000 cm⁻¹. For electrical characterization, aluminum gate silicon nitride MNS capacitors were fabricated.

Post-deposition annealing (PDA) was carried out for 20 min at 850 °C in a three-zone proportional integral derivative (PID) temperature-controlled furnace in nitrogen atmosphere. Front and back metallization was carried out by e-beam evaporation. A metal mask of area 1.96×10⁻³ cm² was used for defining the gate area. Post-metallization annealing (PMA) was carried out for 20 min at 420 °C in a three-zone PID temperature-controlled furnace in nitrogen atmosphere. High-frequency C–V measurement of MNS capacitors was carried out with an Agilent 4263B LCR meter (100 Hz–100 kHz) with a Keithley 175 auto ranging multimeter and an Agilent 8631A power supply interfaced to a Pentium II processor through a GPIB card.

3. Results

Fig. 1 shows the variation of the integrated intensity of the Si–N and N–H bands for various nitrogen dilutions determined from FTIR spectra. The area under the absorption peak related to Si–N vibration at 840–880 cm⁻¹ is proportional to the number of Si–N bonds. As shown in Fig. 1, the Si–N integrated intensity increases with N₂ dilution. This indicates that N₂ dilution facilitates Si–N alloying. Simultaneously, the number of N–H bonds also increases with N₂ dilution.

The high-frequency C–V forward and retrace characteristics are shown in Fig. 2. The current density–electric field (J–E) characteristics of the MNS capacitors are shown in Fig. 3. Fig. 4 shows the time-dependent dielectric breakdown (TDDB) curves for films with different nitrogen flow rates. The film with maximum nitrogen dilution of 50 sccm shows high breakdown field strength and the current almost remains constant for the entire period of 5000 s at a stress field of 10 MV cm⁻¹, indicating almost no trap generation in the film.

4. Discussion

There are several observations to be made from the C–V and I–V measurements:
Fig. 4. Please supply caption.

i. The thickness as determined from the C–V curves is in the range of 4.2–3.8 nm, meaning that the deposition rate is not drastically affected in this N₂ dilution range.

ii. The fixed charge density decreases from $5 \times 10^{12}$ to $8 \times 10^{11}$ cm⁻² as N₂ flow varies from 10 to 50 sccm.

iii. A small hysteresis observed in the retrace C–V data taken after a time delay of 3 min (during which the device is under bias) indicates negligibly small border traps.

iv. The breakdown field increases with increasing N₂ flow and is beyond 12 MV cm⁻¹ for high-dilution films.

v. The leakage current density decreases from $4 \times 10^{-6}$ to $1 \times 10^{-8}$ A cm⁻² with increasing nitrogen dilution.

From the results we observe that nitrogen dilution of the SiH₄+NH₃ mixture leads to improvement in the electrical performance of the MNS devices, in terms of fixed charge and breakdown field, as reflected from HF C–V and DC J–E measurements. The increase in the Si–N bond density with increasing nitrogen dilution could be one of the factors responsible for the better electrical performance of the dielectric. The decreased deposition rate may also be responsible for the improvement in material properties.

5. Conclusion

We have looked at the effect of nitrogen dilution of silane on the physical and electrical properties of ~4-nm-thick hot-wire-deposited a-SiN:H films. Nitrogen dilution is beneficial and leads to a significant decrease in the leakage current and fixed charge density. The small hysteresis observed in all the films indicates negligible border traps in these films. Finally, evaluation of the reliability of these MNS capacitors with ultrathin HWCVD nitride deposited with different nitrogen dilution (~2.0 nm of EOT) shows high breakdown fields and very little trap generation in the film during stressing at 10 MV cm⁻¹ for 5000 s.

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References