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Research paper

Dielectrics stability for intermediate BEOL in 3D sequential integration

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3D sequential integration, such as CoolCube™, allows to stack vertically layer of devices. Levels of interconnection, also called intermediate Back-End-Of-Line, are needed between successive layers of transistors to avoid routing congestion. Thus, thermal stability of the dielectrics must be studied in order to fulfil the CoolCube™ requirement: at least to be stable up to 500 °C during 2 h. Consequently, the stability of several barrier layers and oxide based materials has been studied through optical characterizations (ellipsometry, Fourier Transform InfraRed spectroscopy and ellipsometric–porosimetry). SiCO (k = 4.5), in replacement of standard SiCNH (k = 5.6) material as barrier layer seems very promising. Regarding the inter-layer dielectric stability, the state-of-the-art porous SiOCH (k = 2.5) stays suitable for a thermal budget of 500 °C, 2 h.
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1. Introduction

3D sequential integration consists in stacking layers of transistors processed sequentially on top of each other, allowing very high 3D via density and gains in power and performance [1]. With this technology, 3D via pitch can reach 100 nm and below while alignment capabilities currently limit 3D packaging solution to 1 μm pitch. By moving in 3D, the chip area gets smaller with the same number of transistors [2,3]. However, this approach requires the need to rout the bottom tier with the inter-tier Back-End-Of-Line (iBEOL) metal layers to decrease the global routing congestion [3]. As a consequence, BEOL levels need to support top FET thermal budgets (TB). A reasonable maximum thermal budget for top FET has been determined around 500 °C 2 h [4–5] (limit for silicide stability degradation of the bottom MOSFETs). This implies to find solutions to integrate back end material stable above 400 °C. Currently the combination of copper with ULK (Ultra Low-K) materials is widely used for standard BEOL (low resistivity & capacitance, and thus speed improvement). However the integration of such materials in the iBEOL faces a number of challenges. Indeed copper metallization can cause contamination issues in the case of wafer break during the process of the top transistor where FEOL contamination environment is required. Despite the fact that its intrinsic resistance is larger, a solution can be the use of tungsten (W) as it has already been integrated in the FEOL of several products. Previous study highlights that metal lines in copper or tungsten seem to support this TB in terms of capacitance, leakage and resistance [5] but the thermal stability of inter-level dielectrics requires further study. Indeed, the impact of TB on the robustness of the dielectrics is also a significant parameter. The modification of ULK structure [6] and permittivity during a thermal anneal at temperature higher than 500 °C may increase the leakage and delays of the iBEOL and thus degrade the circuit performances.

In this paper, the thermal stability of various inter-metal dielectrics is examined for the barrier layer and the inter-layer dielectric (ILD). The objective is to determine if the available dielectrics fulfil the 3D sequential integration stability requirements. This work is divided in two sections. The first part is dedicated to the thermal stability study of the barrier layer and the second one deals with the thermal stability of oxide-based materials.

2. Experiment

The thermal stability of five nitride-based materials has been studied and material characteristics are summarized in Table 1: the SiCNH as barrier layer reference, two SiN with different stress (−300 MPa and −3 GPa) and a SiCBN film studied as spacer material in [7]. To complete the barrier layer list, a new material, the SiCO [8], developed by Lam Research, has also been examined. In parallel, three oxide-based materials have been investigated (see Table 2): a state-of-the-art BEOL porous ultra-low-k (ULK) as reference, a SiO_2 deposited by high density plasma

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Table 1
Materials studied as potential barrier layer for the inter-level BEOL.

Name	Permittivity	Characteristics
SiCBN	3.8	[7]
SiCO	4.5	[8]
SiCNH	5.6	State-of-the-art/reference
SiN 1	7	Compressive stress: −300 MPa
SiN 2	7	Compressive stress: −3 GPa

chemical vapour deposition (HDP CVD) and a dense SiOCH-low-k (DLK or Dense LK) used as ILD in the 65 nm node BEOL technology. To mimic the metal 1 BEOL stack, 100 nm of oxide-based material and 20 nm of barrier layer have been deposited on 300 mm silicon blanket wafers. Several annealing, from 450 °C to 600 °C during 2 h, have been performed on each material to reproduce the TB of the top transistor fabrication. Dielectrics thermal stability has been deduced from spectroscopic ellipsometry measurements (allowing to determine film uniformity, thickness and refractive index (RI)) before and after annealing. The RI variations give an idea of the material density evolution. The chemical bonding variation has been studied by Fourier Transform InfraRed (FTIR) spectroscopy on the same samples. The analyses have been performed with a P-polarized, 77°incident light, thus the longitudinal and transversal vibrational modes have been excited. Finally, thin film porosity measurement was carried out by Ellipsometric–Porosimetry (EP) [9] in the visible range using toluene as solvent. The analysis of the refractive index change during the solvent adsorption and desorption allows to deduce the open porosity and pore size distribution.

3. Results and discussion

3.1. Barrier layer stability

Thickness measurement has been detailed for the SiCNH barrier layer in Fig. 1. The uniformity of the SiCNH deposition has been measured, hence the maximal and minimal thickness on the graph. After a TB at 600 °C during 2 h, the thickness measured is below the minimal value measured before. Thus, the barrier layer shrinks by 9.6% during the annealing. Thickness variations versus thermal annealing have been compared for each nitrogen based materials, as illustrated in Fig. 2. After the targeted 500 °C, 2 h annealing, the SiCBN and the SiCNH materials are the most impacted whereas the slight compressive SiN (SiN 1) and the SiCO stay stable up to 600 °C 2 h.

In order to understand the thickness variation versus the thermal budget, FTIR analysis was performed on each material. Fig. 3 illustrates the SiCNH chemical bonds variation before and after each TB. The Si—H bonds (peak position: 2000–2260 cm^{-1} [10]) decreases strongly when the TB increases.

The C—H bonds (peak position: 2800–3000 cm^{-1} [10]) are slightly more resistant to 500 °C, 2 h annealing. At higher temperature, a strong variation is observed. The transverse optic Si—N bonds (peak position: 800 cm^{-1} [10]) stay constant whereas the longitudinal optic Si—N bonds (peak 1050 cm^{-1}) increase after the first TB and is shifted to

Table 2
Materials studied as potential oxide-based layer for the inter-level BEOL.

Name	Permittivity	Characteristics
ULK	2.5	Porous ULK
DLK	3	Dense LK
SiO_2	4.1	HPCVD

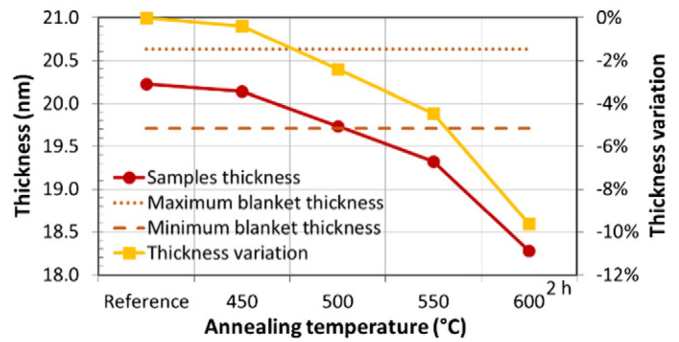

Fig. 1. Thickness measurement of SiCNH materials before and after TB. The minimum and maximum thickness measured on blanket wafer is also plotted on the graph.

the high wavenumber with higher TB. Thus, the quantity of Si—N bonds are preserved but the layer morphology evolves with TB. On Si—N absorption band two negative contributions appear, both are relative to a wrong reference sample compensation (at 1232 nm due to an interfacial native oxide differences and at 1103 nm due to interstitial oxygen from the bulk substrate). The chemical bonds variation, extracted by integration, is illustrated in Fig. 4. The hydrogen chemical bonds decrease versus annealing whereas the peak area mainly attributed to Si—N bonds is not significantly modified. Thus, the outgassing creates dangling bonds which are not filled, increasing the instability of the SiCNH.

With the SiCBN material, B—H bond (peak position: 2450–2650 cm^{-1} [10]) are also identified by FTIR (Fig. 5). The quantity of bonds decreases when the TB increases. A slight hydrogen outgassing is also observed with the SiN1. Finally, FTIR analysis on SiCO only displays Si—O bonds. They are stable versus temperature (Fig. 6). To explain this stability, previous work on this material highlighted that the C is cross linked to the Si [8], which can explain its higher thermal stability. Thus, the loss of thickness for the SiCNH and SiCBN seems directly related to the hydrogen methyl outgassing.

The strong compressive SiN 2 (−3 GPa) has also been studied. After annealing, circular delamination occurred at the surface layer (Fig. 7). The SiN layer, deposited by PECVD, must follow a stress hysteresis behaviour [11]. Thus, during the annealing, the compressive SiN layer tends to change towards tensile values. The native oxide and silicon substrate don't compensate the relaxation. The only way for the film is to locally relax and then delamination occurs. Finally, the delamination shape and uniformity depend on the substrate, deposition condition (frequency) and the interface between the SiN and the substrate.

From these analysis, SiCO and the SiN 1 are the only materials to fulfil the stability requirement: at least be stable up to 500 °C during 2 h. However, thanks to its low permittivity (lower than the state-of-the-

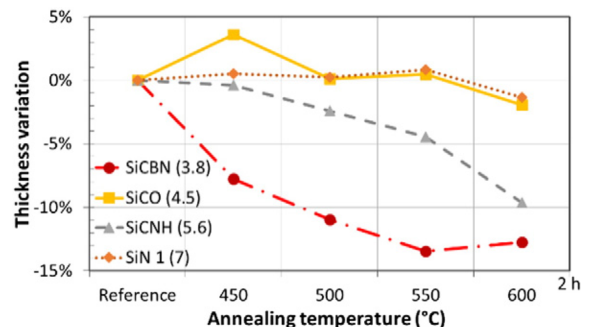

Fig. 2. Thickness variation of all the barrier layers studied after each annealing.

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