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Invited

Fluoropolymer and Aerogel Thin Films as Low Dielection in IC Metallization

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1. Introduction

The reduction of cross talk and signal delay time of interconnects requires the application of low permittivity (low k) dielectrics in sub 0.18 μm technologies [1]. Different types of materials and air gap structures are target of investigation as low k dielectrics including modified CVD SiO_2, silicon and carbon based polymers (CVD, spin on), and porous materials (organic, inorganic). An overview of the state of investigation and the achieved k values is given in Table I. Especially for 0.15 μm technologies and below k values of ≤ 2.5 are believed to be required for the high performance products [2]. These permittivity values are basically achieved with fluorinated polymers deposited by CVD or spin on, porous silicon oxide films (SiO_2 aerogels; also called xerogels) and air gap structures. Latest efforts show also the possibility to fabricate porous polymer films with possible k values in that range. Beside other examples of low k materials the deposition of fluoropolymers and SiO_2 aerogels will be described. Their properties and integration were investigated.

Table I Low k material groups: permittivity and state of evaluation

material (group)	deposition	state	k
SiOF	CVD	qualification	3.4 ... 3.6
Si based polymers HSQ, MSQ, FOX	spin on	qualification	2.8 ... 3.3
C based polymers			
a:CF (fluoropolymers)	CVD	development	2.1 ... 2.6
nonfluorinated	spin on		2.5 ... 3.5
fluorinated	spin on		1.8 ... 3.0
inorganic porous			
SiO_2 aerogel, xerogel	spin on	R&D	1.3 ... 2.2
organic porous	spin on	research	?
air gap structures	PECVD, [spin on]	research	1.5 ... 2.8 (dep. on geometry)

2. Experimental

Fluoropolymer thin films were produced by plasma assisted gas phase deposition in a triode plasma etching chamber (TEGAL 1514e) with NF frequency of 100 kHz applied to the wafer and an HF frequency of 13.56 MHz at pressures of 0.5 Torr using CHF_3 source gas with different additives (CF_4, CH_4, N_2, Ar, NH_3) at about 50°C chuck temperature. Moreover depositions at elevated temperatures (250°C) were performed at an diode RIE chamber using a NF freqency of 300 kHz at 0.3 Torr and C_4F_8 + CH_4 as source gas. To prove thermal stability, the films were treated at different temperatures on a hot plate at air atmosphere for 30 min.

Aerogel thin films were fabricated by a sol gel process from a TEOS and water containing precusor and spin on deposition. Drying of the wet gel was performed by sublimation of the solvent at room temperature and under vacuum. [3]

The films were characterized by thickness measurements (ellipsometry: λ = 632 nm; surface profilometer; cross section SEM), refractive index n, FTIR (Transmittance, Broker IFS48 system), RBS, AES and SIMS. Furthermore, electrical characterization was perfomed by leakage current, breakdown voltage, and CV measurements partly at Al dot structures and partly using a mercury probe equipment (SSM 495). The permittivity was calculated from CV measurements.

3. Electrical and Thermal Simulation of the Application of Low k Dielectrics in Metallization Schemes

Beside the introduction of low resistivity and low permittivity materials the geometry and architecture optimization is important to achieve best switching time improvements for a given cross talk limit (of e.g. 0.5 V_{dd}). The most simple cases for the architecture are low k as interlevel dielectric (IeLD, between metal levels surrounding the vias) and intralevel dielectric (IaLD, beween metal lines) or low k dielectric as IaLD only, staying with SiO_2 as IeLD. More complicated stacks of dielectrics appear if technology needs are taken into account (cap, adhesion, etch stop layers etc.). Electromagnetic field simulation was used to estimate the performance gains in terms of swiching time improvement

$$\mathrm{SWTI} = \left[\frac{1/\tau - 1/\tau_{ref}}{1/\tau_{ref}} \right] * 100\,\% \qquad (1)$$

of different dielectric stacks for given cross talk noise and geometry (metal 1 of 0.18 μm technology) taking into account a multiconductor configuration [4]. Especially for narrow lines (< 0.25 μm technology) the switching time is dominated by the line-to-line capcitance. The SWTI introducing aerogel with a k value of 1.7 as IaLD is up to 100% depending on line length (see Fig. 1). Even for short lines of about 100 μm a SWTI of 40% is achievable. The destinct to complete use of low k dielectric for IeLD and IaLD is minimal.

A very important issue with low k dielectrics is the heat dissipation. The (much) lower heat conductivity of the low k materials compared to SiO_2 can lead to temperature increase of metal lines. FEM simulation was used to verify the influence of low k integration on metal line temperature. Application of materials with a heat conductivity of 10^{-3} of that of SiO_2, for instance, would lead to an increase of the line temperature rise by a factor of 30. In contrast if such materials are used only as IaLD this increase is neglectible. The possibility to use low k materials only as IaLD can make integration easier.

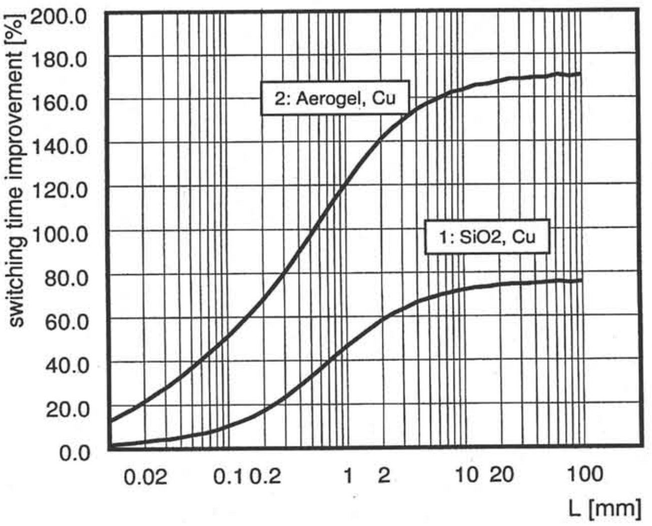

Fig. 1 Switching time improvement by using Cu/SiO_2 (1) and Cu/aerogel IaLD (2) compared with Al/SiO_2 metallization. Reference design assumptions are taken from 0.18 μm CMOS technology metal 1, ρ_{Al}=3.7 μΩcm, ρ_{Cu}=2.1 μΩcm, driver resistance = 50 Ohms, load capacitance = 5 fF.

4. Properties of Fluoropolymer Thin Films

Fluoropolymer films deposited from CHF_3 showed good adhesion on Si substrate, refractive index of 1.36 to 1.42 (except addition of CH_4), low permittivity of 2.1...2.25 but low thermal stability (thickness loss of up to 10% during annealing at 250°C). The addition of CH_4 leads to increased thermal stability but also increased k. The films showed excellent electrical properties e.g. for films deposited from CHF_3/CF_4 : k = 2.1, E_{bd} > 5...7 MV/cm, I_{leak} < 10^{-13} A/cm². A good gap fill capability was achieved over RIE patterned Cu lines.

Improved thermal stability (thickness loss below 1%) up to 350°C was found for films deposited at elevated temperatures from $C_4F_8 + CH_4$. The permittivity of these films was 2.3...2.5. The leakage current of such fluoropolymers in the as deposited state is comparable to that of thermally grown SiO_2 (see Fig. 2). It remains below 10^{-12} A/cm² for annealing at 250°C.

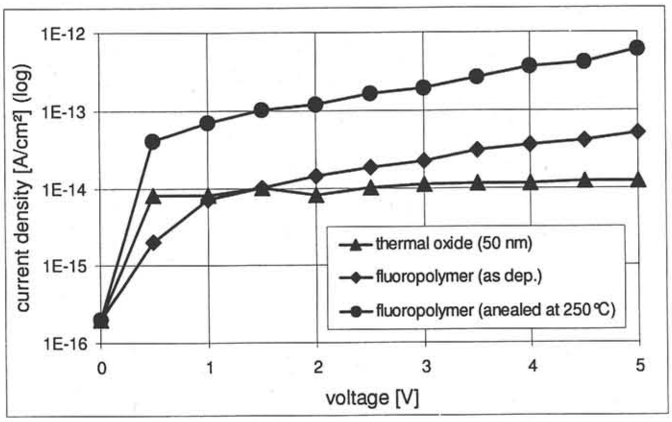

Fig. 2 leakage current density of fluoropolymer compared to SiO_2

5. Properties of SiO_2 Aerogel Thin Films

The deposited films have a ratio of Si:O:H of 1:2:0.28 measured by RBS and ERD. The porosity is tunable and was set to 67% for most of the investigations. The resulting permittivity was about 2.0 (@ 1 MHz). The nanoporous film was uniform over the entire thickness (see XTEM in Fig. 3) with pore size below 10 nm. The mean surface roughness was determined by AFM to 0.34 nm. The material showed a surface area of 450 to 500 m²/g (measured by BET at a bulk sample). Very few appearing C-H bonds and water in the films were found by FTIR and Raman spectroscopy (content of carbon in C-C and C-H bonds < 1%. The aerogel films remained stable at heat treatments up to 700°C for 1 h in vacuum without changing thickness and refractive index (1.12...1.22). RIE etching with up to 600 nm/min was achieved by using hard mask. Further process and material compatibilty issues will be discussed.

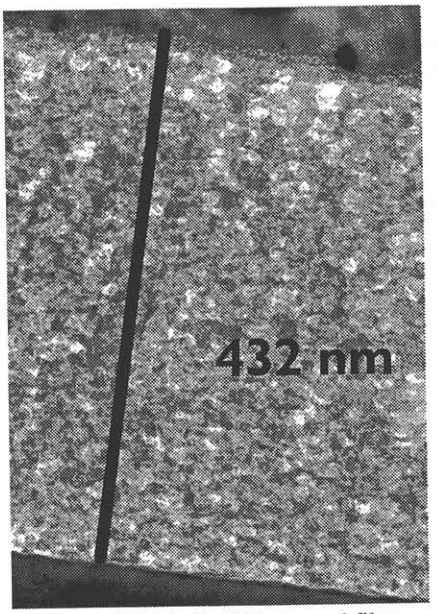

Fig. 3 XTEM of a SiO_2 aerogel film

6. Conclusions

The application of low k dielectrics as IeLD is favorable from thermal considerations and nevertheless yields high switching time improvement. Fluoropolymers deposited by CVD show acceptable thermal stability, excellent electrical properties and good gap fill capability. SiO_2 aerogel films with ultra low k combine proven material with pore sizes much below feature sizes and high thermal stability.

References

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Acknowledgments

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