Available online at www.sciencedirect.com
ScienceDirect
Thin Solid Films 516 (2008) 3558–3563
www.elsevier.com/locate/tsf

Plasma ash processing solutions for advanced interconnect technology

N.C.M. Fuller [a,*], M.A. Worsley [b], L. Tai [c], S. Bent [d], C. Labelle [e], J. Arnold [f], T. Dalton [a]

[a] IBM Research Division, T.J. Watson Research Center, Yorktown Heights, NY 10598, United States
[b] IBM Research Division, Yorktown Heights, NY 10598 and Stanford University, United States
[c] IBM Systems and Technology Group, Hopewell Junction, NY 12533, United States
[d] Department of Chemical Engineering, Stanford University, Stanford, CA 94305, United States
[e] Advanced Micro Devices, Hopewell Junction, NY 12533, United States
[f] Semiconductor Research and Development Center, IBM Research Division, Albany, NY 12222, United States

Available online 23 August 2007

Abstract

A mechanism for the modification of porous ultra low-*k* (ULK) and extreme ultra low-*k* (EULK) SiCOH-based materials is proposed. This is achieved by correlating film damage on a patterned structure measured by angular resolved x-ray photoelectron spectroscopy (ARXPS) with corresponding changes in reactive species radical density and ion current in the plasma measured by optical emission spectroscopy (OES), rare gas actinometry, and modeling. Line-to-line electrical leakage and capacitance data of nested line structures exposed to downstream ash plasmas suggest that other etching steps during back-end-of-the-line (BEOL) dual damascene processing are also critical for the overall modification induced to these materials.

Keywords: Plasma modification; Ion current; Porous SiCOH dielectrics; Downstream plasmas

1. Introduction

The employment of SiCOH-based inter-level dielectric (ILD) materials for 90nm and beyond CMOS back-end-of-the-line (BEOL) technologies has been a key enabler for increased integrated circuit (IC) performance. However, this "paradigm shift" from Al/SiO_2 to Cu/SiCOH-based interconnects has not occurred without many integration challenges; including the critical issue of plasma-induced ILD modification. This phenomenon occurs upon exposure of the ILD material to plasma processing conditions [1–3]. During this process, reactive radical species in the plasma chemisorb onto chemically and/or physically activated dielectric sites (surface and bulk) modifying the stoichiometry, density, and/or physical structure of the dielectric. Macroscopically, these changes culminate in increased hydrophilicity, dielectric breakdown (leakage), and dielectric constant (capacitance). An example of the consequence of this modification process is depicted in Fig. 1 which shows SEM images of a 1st metal level SiCOH build ($k \sim 3.0$) post processing with an un-optimized ash process and post exposure to dilute HF (for removal of the carbon-depleted "oxide-like" modified layer). The latter SEM image reveals a 10 nm undercut at the hardmask-ILD interface indicative of the degree of ILD modification induced primarily by the ash process (in this instance). The effect exhibited in Fig. 1 is potentially exacerbated for porous SiCOH-based ILDs. Thus, with the continued evolution of CMOS technology (for even higher performance ICs) charted to include interconnect structures partially comprised of porous SiCOH materials ($k \leq 2.4$), the demand for increased understanding of this mechanism(s) and for finding plasma ash solutions for future BEOL technology nodes is critical.

Though there has been substantial work to date to elucidate on the key mechanism(s) responsible for this modification process, much of it has focused on using blanket wafer analysis [4–6]. While such studies are indeed useful for determining generic mechanism(s) for film modification upon plasma exposure, analysis of patterned structures is necessary to completely understand the dominant mechanism(s) responsible for the ILD modification process during dual damascene processing [7–10].

* Corresponding author. Semiconductor Research and Development Center, IBM Research Division, Yorktown Heights, NY 10598, United States.
E-mail address: nfuller@us.ibm.com (N.C.M. Fuller).

0040-6090/$ - see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.tsf.2007.08.071

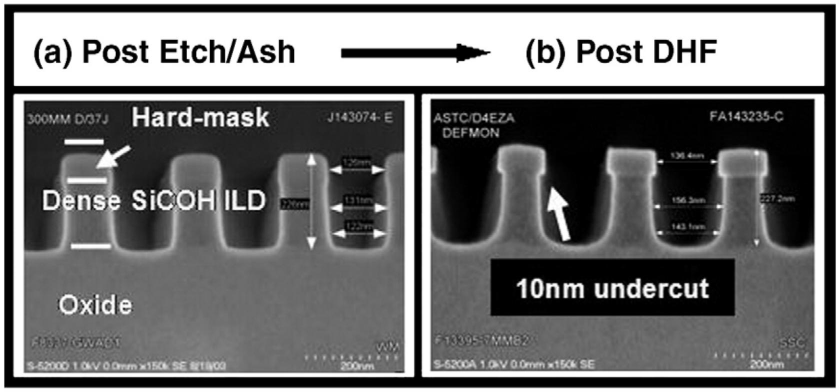

Fig. 1. SEM Images illustrating metal 1 trench profiles: (a) post processing using an un- optimized ash process and (b) post DHF exposure.

To these ends, ARXPS of EULK ($k \sim 1.8$–2.0) porous-SiCOH spin on dielectric (SOD) single damascene builds exposed to miscellaneous plasma ash conditions was conducted. Each of these plasma conditions was characterized by OES, rare gas actinometry, and modeling to determine reactive species radical densities, relative ion current, and relative ion angular distributions (IADs) [11]. Correlation of "damage" measurements on the ILD with corresponding changes in the plasma was facilitated in this manner. Intra-level electrical leakage and capacitance and electron energy loss spectroscopy (EELS) analysis were also conducted on EULK ($k \sim 2.0$) porous SiCOH SOD single damascene builds exposed to a variety of downstream plasma ash conditions. Dilute HF "staining" of dual damascene ULK porous SiCOH ($k \sim 2.4$) builds exposed to alternative ash chemistries and approaches was also conducted.

2. Experimental details

The test structure utilized to examine EULK ($k \sim 1.8$–2.0) porous SiCOH ILD modification by ARXPS has been discussed previously and will not be reviewed here [8,10]. OES and rare gas actinometry were used to measure reactive species density and modeling was used to determine the relative ion current and relative ion angular distribution (IAD) in O_2, N_2, H_2, and NH_3 dual frequency capacitive plasmas on a commercial tool with bias and source powers coupled at 13.56 MHz and 162 MHz respectively. Table 1 shows the wavelengths and energy thresholds of all the species employed for rare gas actinometry measurements. ARXPS of 400 nm (depth) × 280–300 nm (width = critical dimension) etched trenches was used to measure film modification of EULK films ($k \sim 1.8$–2.0) as determined by C:Si, O:Si, and N:Si ratios. Electrical line resistance, intra-level capacitance, intra-level leakage, and EELS of EULK ($k \sim 2.0$) porous SiCOH builds were measured on interdigitated comb-serpentine structures ≤3 m in length exposed to plasma ash conditions on a commercial downstream ash tool powered with a microwave source. Dilute HF "staining" of ULK ($k \sim 2.4$) porous SiCOH builds exposed to alternative ash chemistries (on the same commercial dual frequency capacitively coupled tool as that described above) and/or ash approaches was determined using 100:1 or 200:1 concentrations.

3. Results and discussion

3.1. Investigating plasma induced damage

Fig. 2 shows the percentage dissociation vs Ar fraction for Ar/X_2 discharges (where X=O, N, and H) for a chamber pressure of 30 mTorr and applied powers of 300 W_{162}/200 $W_{13.56}$. The percent dissociation irrespective of Ar fraction is <20% for all plasmas with the H_2 plasma being the most dissociated (10–16%) and the N_2 plasma being the least dissociated (<2%). The minimal dissociation in each of these plasmas can be attributed to the relatively high dissociation bond energy thresholds of each of these gases (H_2: 4.5 eV, O_2: 5.1 eV, and N_2: 9.7 eV), the low electron temperature (T_e) of the plasma (<2 eV), the moderate to high atomic recombination rate on the chamber walls, and the relatively low electron impact dissociation cross sections for each of these species ($<10^{-17}$ cm^2) for electron energies <13 eV [11]. As a function of Ar fraction, only the O_2 discharge shows a significant response with the percentage dissociation increasing by a factor 40× from 0.1% to 4.0% as Ar fraction is increased from 0% to 86%. A corresponding order of magnitude increase in the atomic oxygen densities is observed under these conditions [11]. These changes can be explained by the contribution of Ar metastables to the dissociation process — Penning dissociation [12]. For the N_2 and H_2 plasmas, an expected decrease in atomic nitrogen and hydrogen densities is observed for similar increases in Ar fraction. Thus, Ar fraction can be used to significantly tune the reactive species concentrations of these plasmas to determine the effect this parameter has on modification of the EULK ($k \sim 1.8$ to 2.0) porous SiCOH film.

Table 1
Wavelength, energy threshold, and actinometers for some of the species employed for actinometry measurements

Species	Wavelength, λ (nm)	Energy Threshold, E_{th} (eV)	Actinometer
O	844.6	11.0	Kr $2p_2$
N	821.6	11.8	Kr $2p_2$
H	656.3	12.1	Kr $2p_2$
N2	357.7	12.5	Kr $2p_5$
Kr ($2p_2$)	826.3	12.2	N/A
Kr ($2p_5$)	758.7	11.7	N/A