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Etching Process Scalability and Challenges for ULK Materials

T. Chevolleau[1], N. Posseme[2], T. David[2], R. Bouyssou[3], J. Ducote[3], F. Bailly[3], M. Darnon[1], M. El Kodadi[1], M. Besacier[1], C. Licitra[2], M. Guillermet[3], A. Ostrovsky[3], C.Verove[3] and O. Joubert[1]

[1]CNRS/LTM (CEA/LETI- Minatec), 17 rue des martyrs, 38054 Grenoble cedex 09, France
[2]CEA, LETI, MINATEC, F38054 Grenoble, France
[3]STMicroelectronics, Central R&D, 850 rue J. Monnet, 38926 Crolles cedex, France
Email: thierry.chevolleau@cea.fr

Abstract

With the scaling down of integrated circuit devices, a constant effort is needed to improve the patterning technologies of interconnect stacks using either the metallic masking strategy or the organic masking strategy. Critical dimensions and profile control, plasma-induced damages (modifications, post etch residues, porous SiOCH roughening) are the key challenges to successfully pattern dual damascene porous SiOCH structures. We have compared the patterning performances of both masking strategies in terms of profile control. One of the main challenges is to optimize the plasma processes to minimize the dielectric sidewall modification. This has been achieved by using optimized or new characterization techniques such as scatterometric porosimetry, infrared spectroscopy, x-ray photoelectron spectroscopy.

Introduction

For the next technological generations of integrated circuits (32 nm and below), the integration of copper/porous low-k in interconnects is one of the key point for device performance, process manufacturability and future scalability. For the interconnection fabrication, dual-damascene patterning is performed by etching trenches and vias into porous SiOCH dielectrics (p-SiOCH). Controlling the profiles of the etched structures and minimizing plasma-induced damages of the p-SiOCH materials are the two main concerns. For the patterning of p-SiOCH, two hard mask strategies (metallic and organic masks) have been developed and implemented over the last decade [1]. These two masking strategies have both advantages and drawbacks in patterning of dual damascene structures. For monitoring the p-SiOCH modifications, many studies have been performed to characterize the modification on blanket wafers which mimic the modification of the bottom of the trenches in dual damascene structures [2]. Few studies have been performed on patterned structures to determine the sidewall modifications while this information is critical and more relevant.

In this work, we address the main patterning issues associated with both masking strategies in terms of profile control. We will also focus on the sidewall modifications induced by the plasma processes using new or optimized characterizations such as scatterometric porosimetry (SP), infrared spectroscopy (FTIR), x-ray photoelectron spectroscopy (XPS).

Experimental

Patterning of single damascene structures (trenches) is performed in a capacitive plasma reactor (CCP) and an inductively coupled plasma reactor (ICP). In this work, the titanium nitride (TiN) hard mask is deposited by physical vapour deposition (PVD) while the organic mask is a spin coated carbon based mask. The dielectric stack is as follows (figure 1): a SiCN layer, a porous SiOCH film ($k < 2.5$, porosity < 30 %) and a SiO_2 capping layer. The two types of mask are deposited on the dielectric stack. For the TiN mask, a bottom antireflective coating is spin coated on the TiN layer prior the 193 nm lithography (figure 1). For the organic mask, a silicon containing layer (Si-ARC) is spin coated on the organic hard mask prior 193 nm lithography. This layer is used as a bottom antireflective coating and also to transfer the photoresist patterns into the organic mask.
After patterning the damascene structures, the sidewall modifications have been characterized by SP, FTIR and XPS [3]. FTIR can determine the loss of methyl from the porous SiOCH sidewalls while XPS gives the composition of the sidewall surface (within 10 nm probing). The scatterometric porosimetry (SP) is a new technique which has been designed specifically for monitoring the porous SiOCH sidewall damages. This technique is a combination of scatterometry and ellipsometric porosimetry. A SP measurement with water as solvent can provide the thickness of the hydrophilic damaged layer on the sidewalls while a measurement with methanol as solvent determines the porosity of the dielectric lines and the permeation of the surface of the sidewalls.

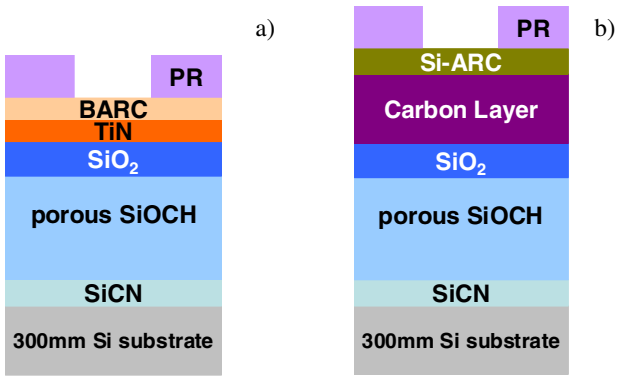


Figure 1: stacks with (a) the metallic masking strategy and (b) the organic masking strategy

Results and discussion

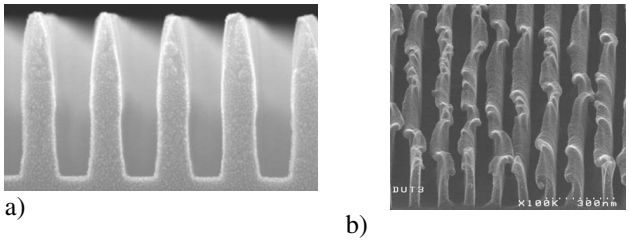
Etching process scalability versus masking strategies

The etching process scalability of both masking strategies has been compared with single damascene structures (M1 level).

The organic masking strategy

The Si-ARC material is etched using fluorocarbon based plasmas and the Si-ARC patterns are transferred into the organic mask with reducing based plasmas (NH_3 or N_2/H_2). Straight profiles can be obtained in the organic mask. After the organic mask opening, the SiO_2, porous SiOCH and SiCN layers are etched in fluorocarbon based plasmas. Straight profiles with a slight bow can be achieved (figure 2). It is worth mentioning that all the etching steps are performed in the CCP reactor.

However profile distortions are observed for trench dimensions lower than 30 nm as shown in figure 2. The profile distortions are mainly attributed to pattern flop over of the organic mask or dielectric during the etching of the dielectric layers. One of the possible ways to avoid pattern flop over, is to both improve the mechanical properties of the mask and the porous dielectric materials [4]. Other studies have proposed to use UV cure after organic layer openings or optimized p-SiOCH etch chemistries [4, 5]. In addition, the organic masking strategy involves a stripping step using either oxidizing chemistries or reducing chemistries to remove the remaining organic mask after dielectric patterning. Such strip processes generate sidewall damages of porous SiOCH trenches.



a) b)

Figure 2: (a) Trench profiles (pitch 70/70 nm) with the organic mask and (b) patterns flop over of the organic mask for narrow dielectric lines (< 30 nm)

The metallic hard mask strategy

After the BARC opening step, the photoresist patterns are transferred into the TiN mask using a Cl_2 based chemistry. The remaining photoresist is removed using an O_2 plasma. All the etching steps are performed in the ICP reactor. After the TiN opening steps, the SiO_2, porous SiOCH and SiCN are etched using fluorocarbon based plasmas in the CCP reactor. Straight profiles with a slight bow are obtained (figure3).

However, patterning of sub-50 nm p-SiOCH trenches can lead to severe profile distortions attributed to the undulations of the dielectric lines (figure 3). This phenomenon, so called wiggling, is explained by the compressive residual stress into the TiN mask (>2 GPa) and the low elastic properties of the porous dielectrics (*young modulus* < 7 Gpa). Experiments and mechanical simulations show that undulations originate from buckling of the porous dielectric lines which allows the release of the strain energy initially stored in the TiN layer. Based on these simulations, the use of a low residual stress TiN (< 1GPa) will allow achieving trench dimensions down to 30 nm.

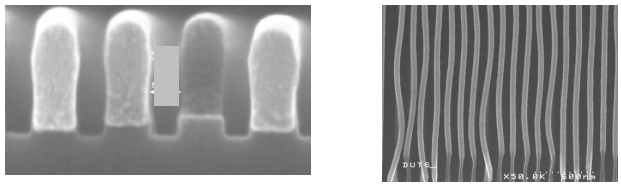


Figure 3: (a) Trench profiles (pitch 70/70 nm) with (a) the metallic mask and (b) wiggling phenomenon of dielectric lines (< 50 nm)

With the TiN masking strategy, the formation of post etch residues has been evidenced after patterning of porous SiOCH (figure 4). The presence of Ti based residues prevents a conformal copper deposition inducing via and line opens and consequently yields loss (figure 4). The growth of such residues (metallic salt) is air exposure time dependent and results from complex chemical reactions between the fluorocarbon covered TiN surfaces and air moisture [6]. One of the solutions to prevent the residue formation is the implementation of post etching plasma treatments (PET) using reducing chemistries (figure 4). With H_2 and NH_3 based plasma treatments, the residue formation is limited by partially removing fluorine species on the TiN mask. With the CH_4 based plasma treatment, the residue formation is stopped by the presence of a thin carbon passivation layer on the top of the TiN mask which probably prevents the complex mechanisms of reaction between fluorine species and air moisture.

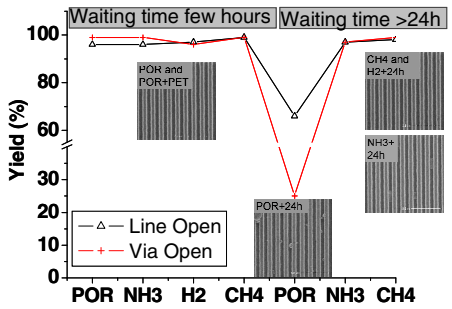


Figure 4: Effect of the different post etching plasma treatments on the line and via yields. Top SEM CD view after etching (POR) and after etching and the different post etching plasmas

Using either the organic mask or the metallic mask, trenches dimension down to 50 nm can be achieved. However profile distortions are expected for sub-50 nm trenches mainly due to mechanical limitations in both cases. For the TiN masking strategy, the development of a layer with a low residual compressive stress is required while it is necessary to improve the mechanical properties of the mask and the porous dielectric for the organic masking strategy. Other emerging issues are the line edge roughness of the porous SiOCH structures which may affect the electrical performances and the reliability of the interconnections [7].

Plasma induced porous SiOCH sidewall modification

Porous SiOCH materials are very sensitive to fluorocarbon etching plasmas, stripping plasmas and post etching plasma treatments.

After etching (POR) and the different post etching plasma treatments (NH_3, CH_4, H_2, and O_2), the thickness of the hydrophilic layer formed on the porous SiOCH sidewalls has been estimated thanks to the decoration technique (HF dip) and SP measurements with water (figure 5). First, we observe that the thickness measurements are similar with both techniques. Second, the hydrophilic layer thickness is higher after the O_2 or NH_3 plasmas (20 nm thick) than after etching (10 nm thick) while the thickness of the hydrophilic layer is lower after the CH_4 or H_2 plasmas (below 5 nm thick). This lower thickness can be explained either by a lateral etching of the hydrophilic layer or by creation of a more hydrophobic damaged layer.

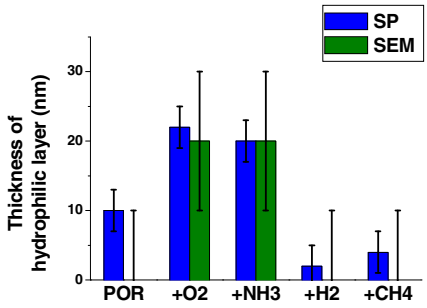


Figure 5: Thickness of the hydrophilic layer of the porous SiOCH sidewalls after etching and different post etching plasmas (estimation of the thickness by SP measurements in blue and with the SEM using the decoration technique in green)

The adsorption kinetics of methanol into the patterned structures have been determined by SP. Figure 6 shows that the porosity of the porous dielectric lines remains the same as the pristine material after exposure to any plasmas investigated in this study. However the surface permeation is slightly lower after etching than after the different plasma treatments. XPS analyses (figure 7) indicate the presence of a fluorocarbon layer on the porous SiOCH sidewalls after etching. This layer is partially removed after the different plasma treatments. Therefore the difference in terms of kinetic of methanol adsorption between the etching and the plasma treatments can be mainly explained by the fluorocarbon layer on the porous SiOCH sidewalls which tends to slow down the methanol adsorption.

Based on these results, the damages of the porous SiOCH sidewalls are unavoidable after plasma exposure. Indeed a hydrophilic layer is present on the porous SiOCH sidewalls which affects the RC value and reliability of the interconnections. One of the emerging solutions is to restore the hydrophobic properties of the modified layer using, for instance, silylation based processes [8].

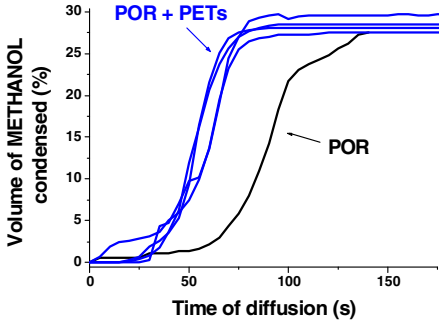


Figure 6: Kinetic of methanol adsorption after etching (POR) and different post etching plasma treatments (PET).

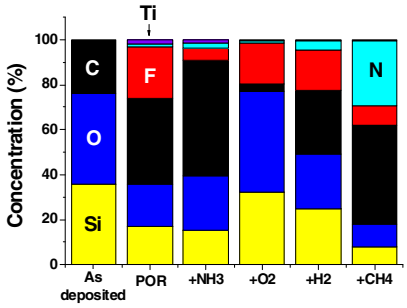


Figure 7: Surface composition of porous SiOCH sidewalls after etching (POR) and different post etching plasma treatments.

Conclusion

The etching scalability of porous SiOCH patterning is not related to conventional profile issues such as tapered or bowed profiles. The scaling down to 50 nm can lead to severe profile distortion due to mechanical constraints (wiggling phenomenon with metallic mask and pattern flop over with organic mask).

In the damascene structure fabrication, the plasma process induces damages of the porous SiOCH sidewalls. Therefore the characterization of sidewall damages is mandatory in order to explore new solutions to minimize or restore the modified hydrophilic layers.

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