Topography evolutions of high aspect ratio sub-micron photo resist trench structure by high-density plasma reactive ion etching patterning

Son. V. Nguyen, Quang Le, Jacquie Latimer and Philip M. Rice
IBM Almaden Research Center, San Jose, California 95120 USA

ABSTRACT

The topographical evolution of sub-micron structure profile during high aspect ratio etching of organic low-K materials with high density oxygenated plasma is predominantly determined by both ion bombardment and lateral radical etching species. The charging effect of various hard masks during etching increases the off-angle positive ion bombardment to the sidewall on top of the etch structure and enhances the profile bowing effect. Lateral etching by radical and off-angle ion bombardment can be reduced by lowering etching substrate temperature or by forming sidewall passivation material during etching.

INTRODUCTION

As the critical dimensions of microelectronic devices drop significantly below half-micron dimensions in semiconductor fabrication, the use of High Density Plasma reactive ion etching processes to form high aspect ratio of low-k material become more critical (1). Many low-k dielectric materials are organic-based polymer and they can be patterned in Nitrogen/Oxygen plasma to form a desirable profile (2) for advanced device fabrication. However significant undercut has been observed in the etch profiles and some passivation chemistry process is required to achieve vertical etch profiles for sub-micron structures of 3:1 aspect ratio (3). In another approach, cryogenic temperatures as low as - 80 degree C has been used in high density Electron Cyclotron Resonance plasma etching of the photo resist to reduce profile undercut by radical lateral etching (4). For Silicon etching, reducing the etching substrate temperature to -120 degree C also significantly minimizes lateral etching (5).

In this paper, we will present our recent results on low temperature high-density plasma etching of high aspect ratio sub-micron organic-based photo resists trench structures with various dielectric and conductor hard masks.

EXPERIMENTAL

High-density inductive coupling plasma equipment was used to study the etching of organic low-K material. The equipment configuration with dual RF source for coil and RF bias is shown in the schematic of figure 1. The etching is implemented at various substrate temperatures from 20 to -60 degree C. For this study, a tri-layer resist/hard mask/resist material structure with various sub-micron openings was fabricated by exposing the top resist layer with a suitable photolithography process as shown in figure 2. The hard mask was then opened by a reactive ion etching process and then the base layer resist was patterned by oxygenated gas. For this study, the hard mask could be either insulating silicon dielectric materials such as silicon oxide or conducting material such as Tantalum. In general, the etching pressure was maintained at 3-5 mT and the flow rate of either oxygen or carbon based oxygenated reactant gas at a 20-40 sccm range. The use carbon based oxygenated gas is used to form a side wall passivation layer during the etching process to modify the etch profile. The dissociation of the reactive species in the discharge is controlled mostly by the coil RF (13.56 MHz) power in the 200-300 Watts region, and the ion bombardment is varied with the substrate RF (13.56 MHz) bias power in the 100-200 watt range. Generally, the plasma RF bias voltage on substrate is maintained in the 300-450 V range to minimize the hard mask sputtering during the etch process. The Monte Carlo method was used to simulate the Oxygen etching profile of the photo resist with a hard mask at various aspect ratios under the above conditions. Focus Ion Beam Etching (FIB), Transmission Electron Microscopy (TEM) and Scanning Electron Microscopy (SEM) techniques were used to study the profiles and sidewall passivation of the tri-layer sub-micron structures.

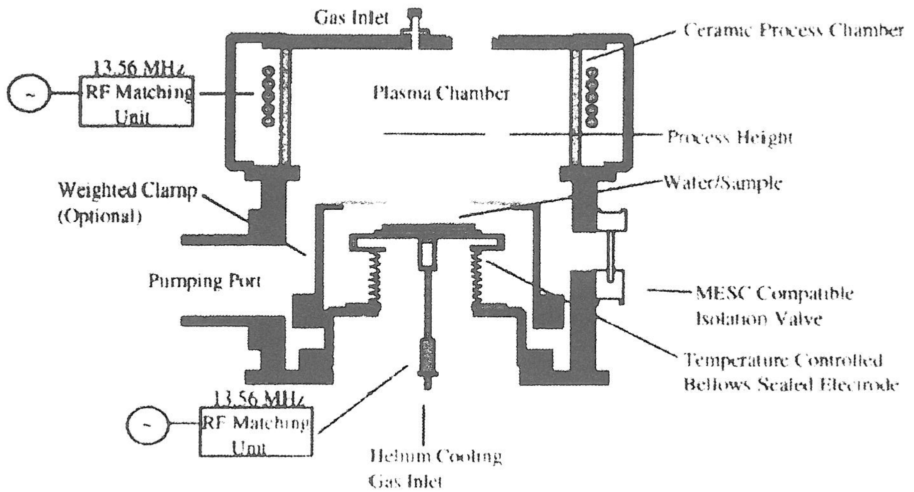

Figure 1- Schematic Diagram of the High Density Plasma Etching Reactor

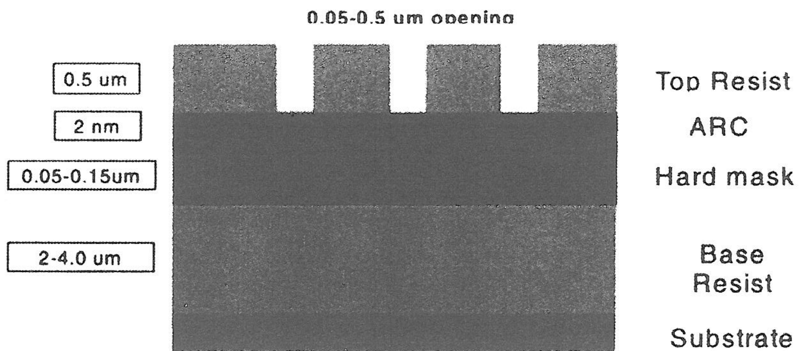

Figure 2- Typical Tri-Layer Resist structure in this etching study

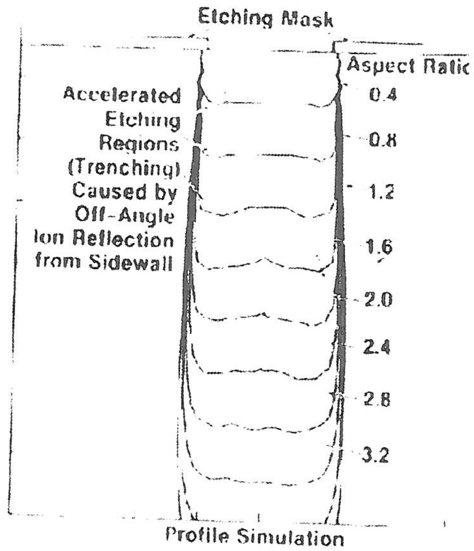

Figure 3- Typical Monte Carlo profile simulation of photo Resist Trench Etching with Hard Mask

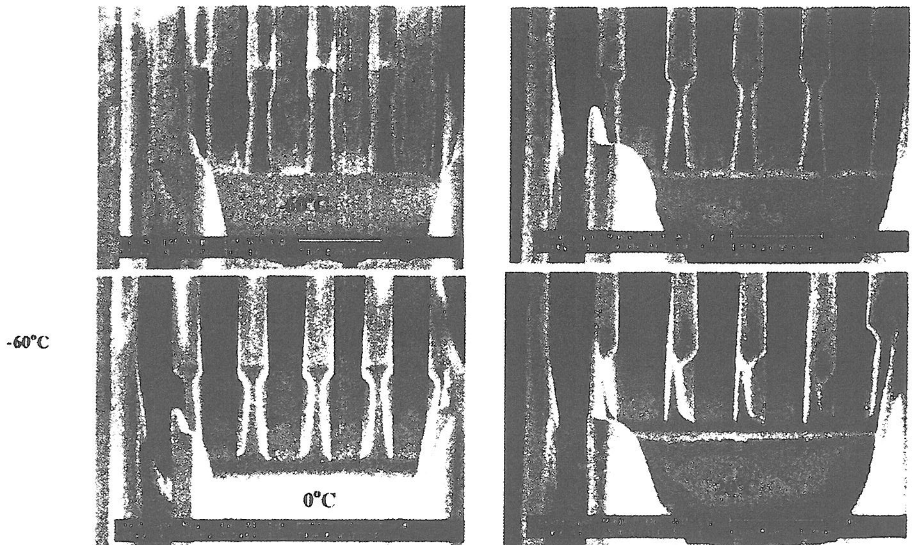

Figure 4A-D. Sub-micron Etch profile with Oxygen Plasma at –60, -30, 0 and 20 C

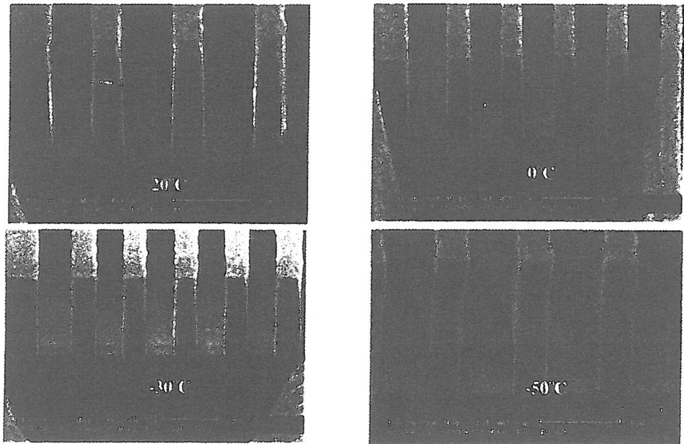

Figure 5A-D. Sub-micron Etch profile with side wall passivation Chemistry at 20, 0, -30 and –50 C

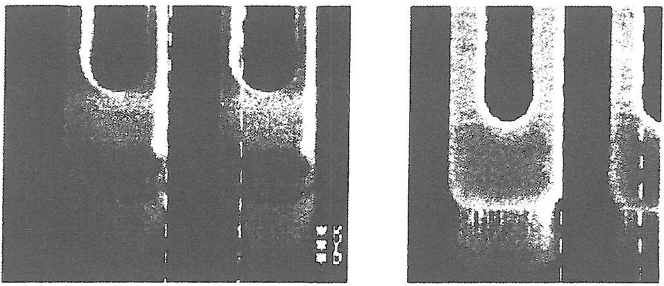

Figure 6A- Insulating Hard Mask Etch Profile Figure 6B-Conducting Hard Mask Etch Profile

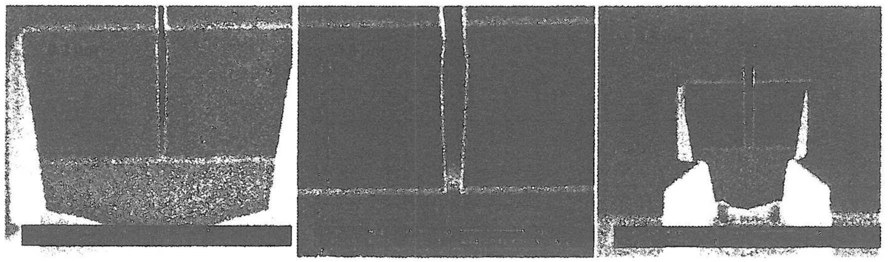

Figure 7A-C – Increasing Bowing in sub-micron Tri-layer structure with higher aspect ratio (i.e. smaller opening) due to larger over etching time

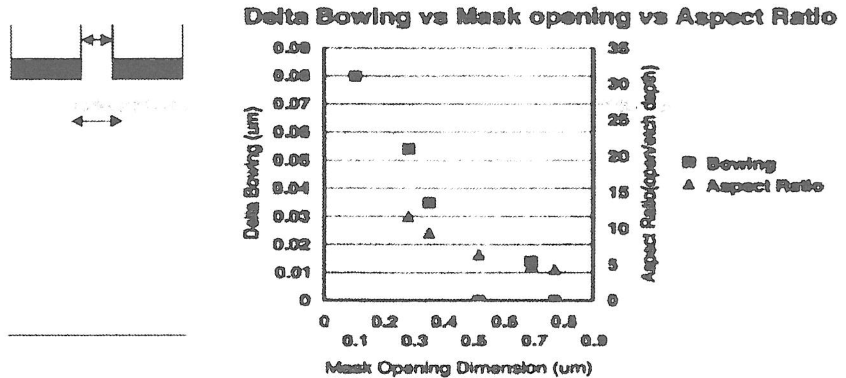

Figure 8 A – Typical Bowing vs Mask Opening and Aspect Ratio in sub-micron Trench structure

RESULTS and DISCUSSION

Overall, lateral etching of the radical and off-angle ion bombardment dominantly determines the topographic profile evolution of the sub-micron trench structure. While vertical ion bombardment plays a dominant role in anisotropic etching of low-K resist, lateral etching by radical will contribute significantly to the etch profile undercut with increasing etching time. Furthermore, the off angle ion bombardment and side wall scattering caused by the collision between the ions and radicals in the plasma dark space (7) and the charging effect (8,9) will also increase trench bowing significantly as the profile evolve with etching time.

Figure 3 showed a typical Monte Carlo simulation etch profile evolution during plasma etching with a hard mask with various etch depths without side wall passivation material. It can be seen from the simulation that the undercut by radical become significant larger with increasing etch depth and aspect ratio. As the etching reaches the bottom endpoint, the etching ions start to scatter off and the etching profile becomes more bowing with increasing etching time. It should be noted that over etching of 25-50 percent is normally implemented during etching of sub-micron structure due to the Reactive Ion Etching Lag effect. Figure 4A-D show the etching profiles of various sub-micron structures patterned with oxygen plasma at substrate temperatures of –60 to 20 C. It can be seen from these pictures that lower substrate temperatures reduce lateral etching by radicals and subsequently reduce the undercut. Forming sidewall passivation layers during etching (3) is another method of reducing the undercut and trench bowing effect caused by radical etching and off angle ion bombardment. Figures 5A-D show the etching profiles of various sub-micron structures patterned by oxygenated carbon plasma with the side wall passivation layer at substrate temperature from –50 to 20 C. It can be seen from these pictures that the side wall passivation etch chemistry reduces the profile undercut and bowing significantly even at 20 C and 35 % over etch time. Lowering the substrate temperature also minimizes the etch profile bowing and undercut further by forming a slightly thicker sidewall passivation layer.

Off-angle ion bombardment in the low-pressure plasma discharge (7) plays a determining role in creating the top bowing etch profile during high-density plasma etching. This bowing dimension is further enlarged by the hard mark charging effect (8) during plasma etching. Figures 6 A-B show the etch profile of the tri-layer structure with insulating and conducting hard masks. Under the same etching conditions, the structure with a conducting hard mask has significantly more undercut and bowing profile on top. During the plasma etching process, the conductor hard mask has more positive charging as compared to the insulating photo resist under layer. This results in more repulsion of positive etching ions from the

conductive hard mask and further enhances the off-angle positive ion lateral etching on the top trench structure. Subsequently, the etch profile becomes more bowing near hard mask layer. For insulating hard mask, there is little or almost no charging effect between the mask and the insulating photo resist layer during etching. As a result, minimal undercut is observed with an insulating mask. For high-density Oxygen plasma etching of very high (>10:1) aspect ratio sub-half micron photo resist trench structure, reduction of etching temperature (up to -60 degree C) will reduce lateral radical etching on sidewall and thus minimize the bowing effect. However, it is still difficult to achieve vertical etch profiles without bowing due to the off- angle ion bombardment. Even with passivation etch chemistry, the off-angle ion bombardment will attack the passivation layer and cause bowing with long over etching times. For structures with high aspect ratio (>10:1) and sub-half micron openings, the larger RIE Lag effect requires much longer over etching times (> 50 %). Subsequently, the top trench bowing increases significantly with etching time as showed in Figure 7 A-C. This top trench bowing increases with smaller openings and increasing aspect ratios as showed in Figure 8A-B. For etching of low-K organic photo resist material, this will cause significant problems for high aspect ratio contact hole filling and subsequent device processing.

SUMMARY

The topographical evolution of sub-micron structure profiles during high aspect ratio etching of organic low-K materials with high density oxygenated plasma is dominantly determined by both ion bombardment and lateral radical etching species. The charging effect of various hard masks during etching increases the off-angle positive ion bombardment in the sidewall on top of the etch structure and thus enhance the bowing effect. Lateral etching by radicals and off-angle ion bombardment can be reduced by lowering the etching substrate temperature or by forming sidewall passivation material during etching. For structure with very high aspect ratios at sub-half micron dimensions, the top trench sidewall bowing , caused by off-angle ion bombardment and charging effects, will increase significantly due to longer over etching times. This bowing will subsequently cause significant problems in device fabrication.

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