# Implementation of Plasma Processing into BEOL with Organic Low-κ Dielectrics

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**Abstract**

The semiconductor industry is continually striving to reduce the dielectric constant of insulators in BEOL materials. Reduction of the constant will in turn reduce current leakage and cross talk between conductor lines, thereby allowing smaller pitch structures to be built onto the device. An organic low-κ material (SiLK$^{TM}$ for example) can be used for the reduction of the dielectric constant, as this type of organic material has a lower constant when compared with traditional inorganic $SiO_2$. Organic functionality within the SiLK material consists of an aromatic hydrocarbon, which has inherent low permittivity that improves resistance to current flow and minimizes cross talk between conductor lines. The material contains no Fluorine or Silicon, and has an as-deposited dielectric constant (κ) of ~2.65 and a glass transition temperature, Tg > 450 °C. The organic content renders the material susceptible to attack upon exposure to conventional oxygen plasma processes. These are used to remove remaining photoresist and residues left on the surface after plasma etching.

Developing a process for resist /residue removal while retaining the electrical and mechanical properties of organic materials and materials with organic content is desirable for current and future BEOL integration schemes. This paper discusses the implementation of SiLK dielectric into the BEOL in IMEC using the Highlands plasma system from Mattson Technology.

**Introduction**

Conventional plasma photoresist removal processes apply oxygen-based plasma to remove residual resist under moderate chamber vacuum (150 mTorr to 5 Torr). An oxygen plasma effectively removes the mostly organic photoresist, yet also may remove mostly (or all) of an organic low-κ film. Going to non-oxygen plasmas can minimize low-κ material removal, albeit at slow rates and with potential feature profile distortion. Mattson Technology has developed the Aspen III Highlands system with an RF plasma source (Fig. 1) designed for low-κ photoresist stripping applications, including residue removal over low-κ/copper structures. During system development, one of the source requirements was to design the tool to be compatible with a wide range of process chemistries. Therefore, this compatibility capability allows process testing of evolving available low-k films without requiring significant hardware changes. This has been an important feature of the Highlands system as low-κ films have ranged from partial to fully organic, with CVD or spin-on deposition techniques. Compatibility of a dry plasma system with SiLK dielectric is important for a back-end ashing process because smaller feature sizes and porous varieties of low-κ films are tested.

Wet process solutions are becoming more challenging due to surface tension effects and the open cell nature of some of the new porous films. This paper will discuss an anisotropic dry plasma solution to this integration scheme.

The Highlands plasma system has a source design that has separate top and bottom electrodes both operating at 13.56MHz. The top electrode is inductively coupled while the bottom electrode is capacitively coupled. Low-pressure operation enables independent control of ion energy (capacitive source) and ion density (inductive source). This allows low-temperature processing with oxygen plasma, as ion energy is now used to lower the activation energy for the strip reaction to proceed at a high rate. This can be contrasted with high-temperature processing; utilizing thermal energy to lower the activation energy in order for the strip reaction to proceed. System operating parameters were optimized with spin on blanket films with organic content on silicon wafers. FTIR results were used to determine the extent of film damage by observation of methyl group peak height retention. Given that the added methyl group functionality imparts less polarity to the film, preserving this organic content minimizes physical and electrical film damage. Once conditions were found which minimized the impact of the plasma on the low-κ film's composition, other low-κ materials were examined with similar results. Early data revealed the importance of low-pressure conditions in maintaining low-κ film properties. With oxygen plasma, low-pressure processes retained the low-κ film's electrical properties with complete resist and residue removal. Further experiments on patterned films was needed; therefore, Mattson partnered with IMEC for some of this work. One of the first Highlands systems was installed in IMEC's semiconductor fab in Leuven, Belgium. The project's goal was to develop solutions to low-κ integration problems using SiLK dielectric. The blanket film data was used to begin the system development in Mattson, Fremont and process development at IMEC. Additional tests at IMEC involved patterns as represented by Fig. 2, a schematic of a Silk structure used in some of the tests. The dielectric SiLK is underneath an oxide hardmask and above a Silicon carbide diffusion barrier layer.

A Joint Development Agreement between Mattson Technology and IMEC has shown the production viability of the Mattson Highlands system. IMEC provided wafer samples, process engineering staff and test equipment to evaluate candidate processes while Mattson Technology provided the plasma system and support staff.



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## Discussion

Before test structures were built, blanket films were used to screen various process chemistries. SiLK dielectric was spin on deposited onto wafers, then subjected to plasma generated in the Highlands system. RI measurements taken at 633-nm wavelength determined the extent of k-value shift.

Test results (see Fig. 3) indicate that a wide range of plasma chemistries are compatible with the low-k material. The table shows the deduced κ-value after exposure to plasma in the Highlands system. Blanket samples were exposed to plasma conditions targeting 5000 Angstroms of resist removal, plus 50% overash. K-value can be calculated as the square of the refractive index at 633nm. From Fig. 3, the reference sample has an RI of 1.634. When squared, this becomes 2.67, which is within 1% of the published value of $\kappa = 2.65$. All the plasma exposed samples fell within 1% of the reference value for κ, indicating that minimal damage to the SiLK film has resulted, even with direct (top down) plasma exposure to the film. In anisotropic plasma conditions, the ion trajectory is normal to the wafer surface. Therefore, on a blanket film, the plasma exposure was calculated as a "worst case" scenario. On patterned wafers, the low-κ film sidewall will be parallel to the ion trajectory, with a resist mask layer and/or hard mask above the low-κ film. The data indicated that multiple passes through the plasma system should have minimal effect on the overall κ-value of the exposed film.

Metal yield tests were defined as a continuity and shorts evaluation of meander fork structures and comb structures, used to test for line integrity and leakage, respectively. These electrical tests were taken on samples after Highlands plasma exposure, which consisted of stripping the photoresist "mask." Quarter micron test structures revealed that the plasma results were essentially equivalent in performance to the advanced plasma etch system used as a reference. With wide variations in plasma chemistry, these electrical results showed that the new plasma process is compatible with organic films. In the first graph, (Fig. 4) the meander structure was tested as resistance along the line/trench. In these tests, $CF_4/H_2$ plasmas were evaluated for stripping and residue removal. Split samples within the lot were compared with and without a wet clean process. There is negligible difference in results with the addition of the wet step, indicating cost saving effects in an optimized integration scheme are possible. The comb structure data (Fig. 5) revealed higher resistance values than the meander structure due to the measurement between lines through the dielectric, as opposed to resistance measurement along the line length in the meander structure case. High resistance here indicated film integrity was preserved in the dielectric. When the results of two splits, one with and one without a wet clean, were compared, there was no significant difference between the splits.

κ-value determination from interline capacitance studies were also carried out. These results (see Fig. 6) confirmed the optical results discussed above, with a final κ-value of ~2.65, which is equivalent to the published as-deposited value given by the material supplier. Structures from 0.25 to 0.4 micron were tested, with plasma-processed wafers exhibiting performance equivalent to or better than the reference plasma etcher process. When comparing the dry processes of splits with and without the wet process, it was found that the wet process may be eliminated or optimized to consume less solvent, water and/or process time. During these interline capacitance studies, CF4 and H2 were found to be compatible with the organic SiLK film. Previous data with $O_2$-based plasma showed similar results on films with partial organic content. Given the compatibility of the plasma process to remove resist and residue from test structures, IMEC used similar processes to also anisotropically remove the silicon carbide diffusion barrier layer.

Preservation of feature profile is an important consideration in this back-end operation and can be seen in Fig. 7, a SEM photo taken after ashing resist from SiLK structures and subsequent copper inlay and CMP. Fig. 8 shows results on patterned SiLK structures after resist ash, residue removal and silicon carbide etch. In both Fig. 7 and 8, it is evident that profiles of the dielectric structure were preserved.

## Conclusions

Based on the optical, electrical, yield and SEM evaluations at IMEC, the Highlands system is continuing to provide good results in BEOL integration projects with organic films. IMEC is currently conducting plasma projects to evaluate porous low-k materials and to show similar performance with the same tool set


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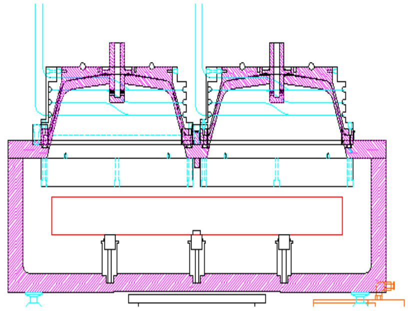


**Figure 1**

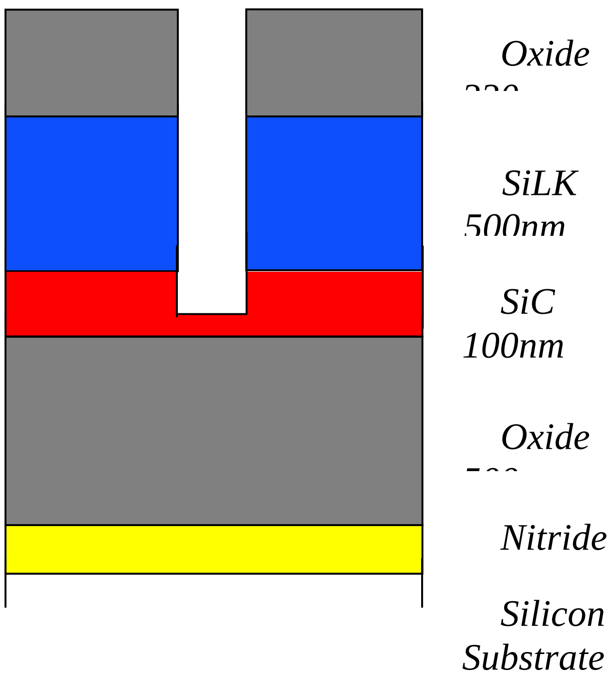



**Figure 2**

**Figure 3**

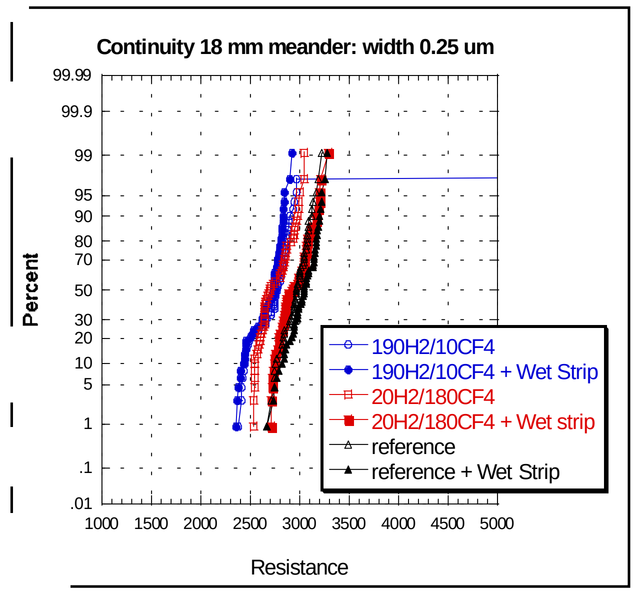
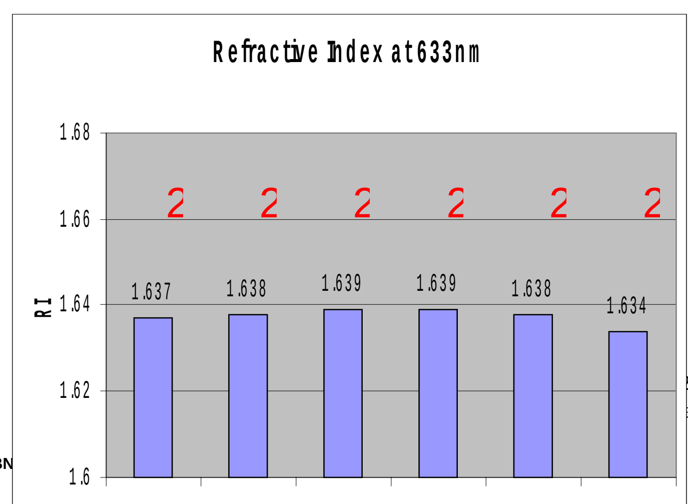
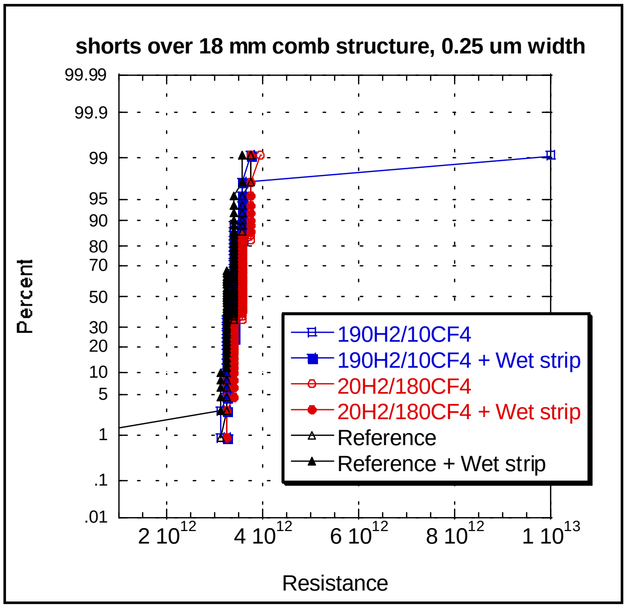



**Figure 4**



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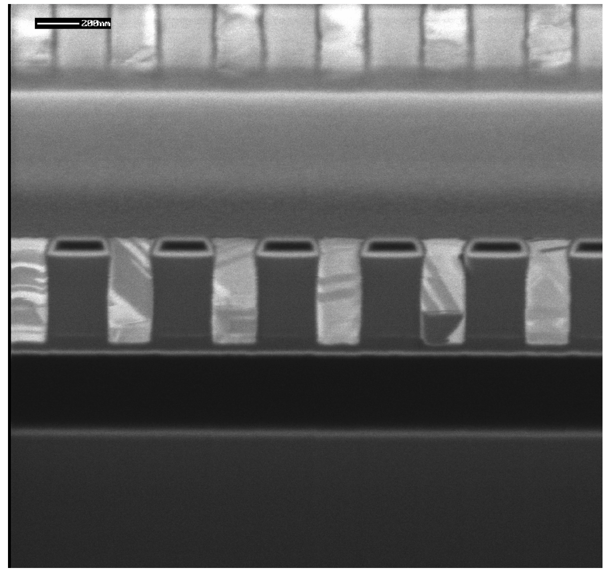

**Figure 7**

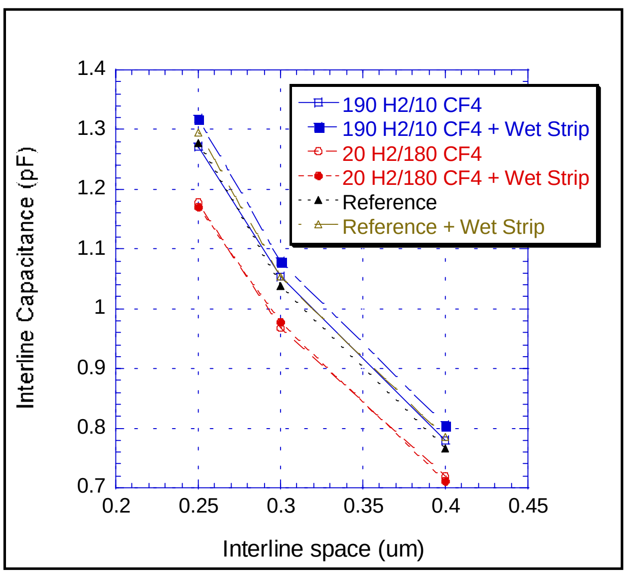


**Figure 6**

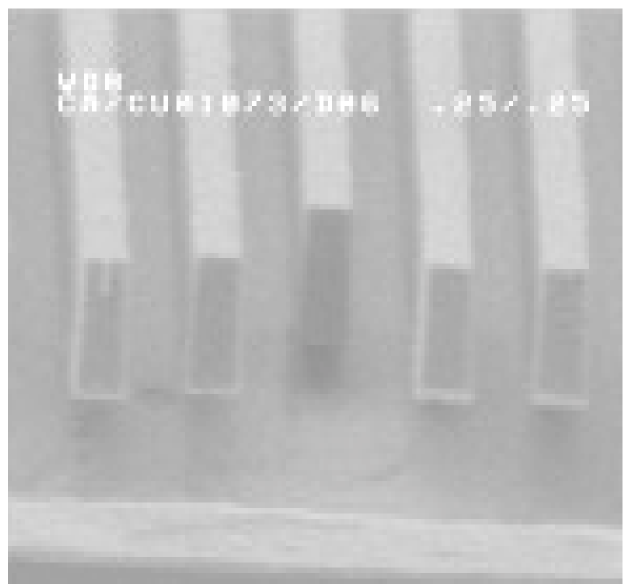

**Figure 8**



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