Direct Patterning of Low-Permittivity Hydrogen Silsesquioxane

As integrated circuits continue to shrink in dimension and evolve into ultra large scale integrated (ULSI) circuit regimes, the minimization of the RC delay in interconnects poses a great challenge. The reduction of the RC delay in integrated circuits can be achieved by using low permittivity (low-k) materials in combination with copper wiring that replaces the traditional SiO_2 and Al in interconnect. At present, the damascene process is the most effective approach that can integrate copper and low-k materials into multilevel interconnect. However, the etching and photoresist (PR) stripping steps will be critical in the damascene process. The etching process, governing the pattern transfer, is more difficult as the pattern becomes much smaller. Also, it has been reported that the photoresist stripping with O_2-based gases can damage the low-k dielectrics.

The direct pattering process with X-ray illumination on low-k dielectrics is capable of solving the above problems, rendering this technique a useful tool in advanced ICs. The advantages of direct patterning are that it can effectively eliminate damages from etching and PR stripping steps and thus reduces the processing steps in Cu damascene process. The X-ray lithography process flow for forming single damascene pattern is shown in Fig. 1. Dual damascene structures can be fabricated simply by doubling hydrogen silsesquioxane (HSQ) deposition/X-ray exposure sequences to produce via and line patterns.

In this study, we will present the pattern images of spin-on low-k HSQ for the first time and examine the applicability of the X-ray direct patterning. Furthermore, the material and electrical properties of X-ray-exposed HSQ will

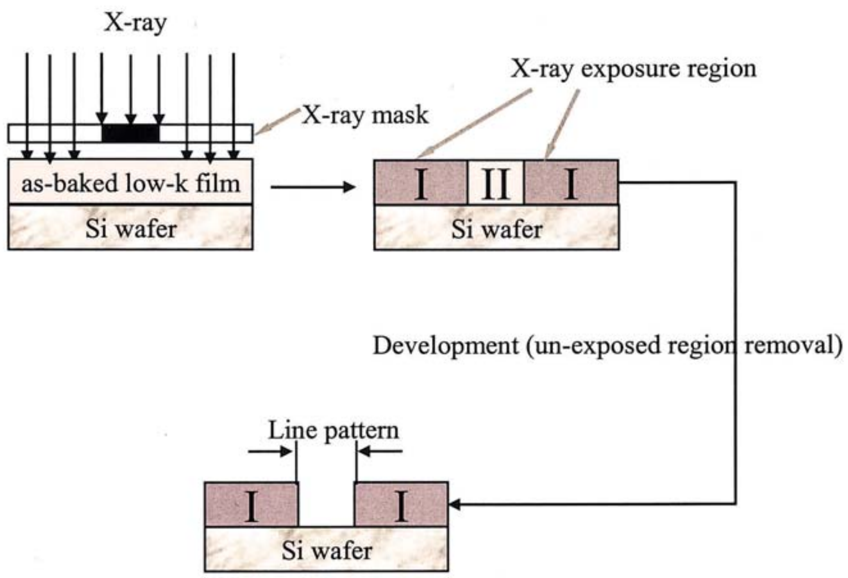

Fig. 1: Scheme of X-ray direct patterning on low-k dielectrics to manufacture the damascene structure. Step I: X-ray illumination on HSQ through a mask (line width ~ 1 µm); Step II: In X-ray illuminated region (I), HSQ is cross-linked. In comparison, HSQ in an unilluminated region (II) remains in gel-like state. Step III: During the development, the region II is dissolved with HSQ solvent while the region I remains unchanged.

be investigated and compared with those from conventional furnace curing process.

The substrates used in this study were 4-in. p-type (11-25 Ω-cm) single crystal silicon wafers with (100) orientation. Before film deposition, the substrates were cleaned in H_2SO_4+H_2O_2 solution at 120 ℃ for 20 min to remove particulates on surfaces. These wafers were spin-coated with low-k HSQ solution at a rotational speed of 2000 rpm for 20 seconds in the model 100CB spin coater. Then, it was followed by sequential baking on hot plates at 150 ℃, 200 ℃, and 300 ℃, for 1 min at each temperature. Afterwards, the wafers were illuminated with X-ray and cured. The X-ray was illuminated through our homemade mask for various dosages that include 10, 20, 30, 40, 50 and 65 W/cm^2. Then, HSQ solvent was used to dissolve the unexposed regions of the HSQ films, and an optical microscope (OM) was used to observe developed patterns. In order to remove the residual organic solvent and enhance dielectric properties of the X-ray-exposed HSQ films, the wafers were transferred to a furnace for a thermal annealing of 1 hour at 400 ℃. In contrast, the X-ray-exposed HSQ films but without being annealed were also studied for comparison. For material and electrical analyses, blank wafers were fabricated by X-ray exposure with previously mentioned conditions without X-ray mask. The infrared spectroscopic analysis was performed from 4000 to 400 cm^{-1} using a Fourier transform infrared (FTIR) spectrometer calibrated with unprocessed wafer, to determining the chemical structure of HSQ films after X-ray exposure. In addition, Al dots were evaporated onto the surface and backside of wafers to manufacture metal-insulator-semiconductor (MIS) capacitance for electrical measurements. The dielectric measurements were conducted using a Keithley Model 82 C-V analyzer. The area of gate electrode was 0.00528 cm^2 for C-V analysis. The current leakage (I-V) characteristics of dielectric were measured by the HP4156 semiconductor analyzer.

In the conventional damascene processes, the photoresist removal is necessary. And, the photoresist removal is implemented typically by utilizing O_2 plasma ashing. However, the dielectric degradation of HSQ after O_2 plasma ashing process often occurs, and has been reported in our previous study. In order to overcome these problems, a novel patterning method using X-ray illumination is proposed in this work. The X-ray lithography technology has superior advantages compared to traditional deep ultraviolet (UV) lithography, including high resolution, high intensity and short exposure time. The dielectric relations between HSQ films and X-ray exposure were investigated for the benefit of academic and industrial communities.

Figure 2 shows the FTIR spectra for the HSQ films that have been exposed to X-ray of different doses. The FTIR spectra indicate that the chemical structures of the low-k films can change significantly, particularly after a high X-ray dosage. For low dosage of the X-ray, the FTIR spectra of HSQ films are almost the same as that for as-baked HSQ. For the increasing dosage, a gradual IR intensity change of functional groups in HSQ films is noted. The intensity of Si-O cage-like peak decreases gradually, whereas the intensity of network-like peak increases. This clearly shows that X-ray exposure transforms the HSQ films from possessing a cage-like structure to having a network structure. In contrast, the HSQ films without being exposed to X-ray remain in gel-like states and are dissolvable in their own solvent. Therefore, after development with HSQ

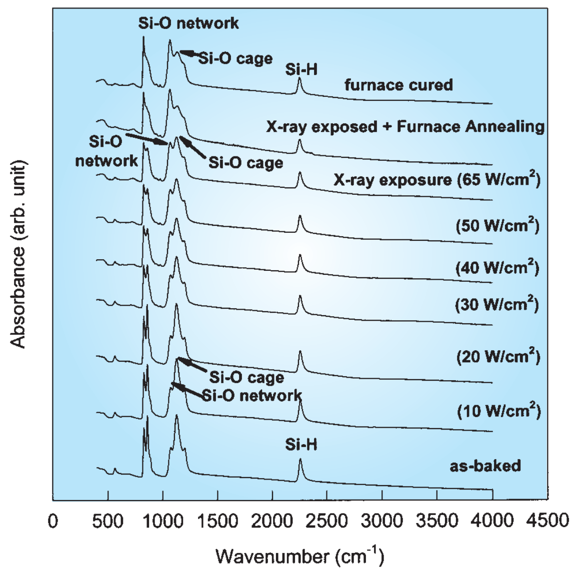

Fig. 2: FTIR spectra for the HSQ films exposed to X-ray of different dosages.

solvent, the unexposed region can be removed by utilizing high degree of dissolution so as to achieve the desired dielectric patterns. To verify the applicability for a direct patterning on low-k HSQ films using the X-ray exposure, we patterned HSQ films through a homemade mask with a pattern width of 1 μm. In the near future, a pattern with an even smaller width (< 100 nm) will be demonstrated in our forthcoming articles. Figure 3 shows the image of a line pattern formed by X-ray direct patterning method. The successful patterning of HSQ films is achieved. The regions illuminated by X-ray stay put while the unilluminated regions are dissolved with HSQ solvent.

Dielectric constants and leakage current density of HSQ films after X-ray exposure were also evaluated. Figure 4 shows a comparison of dielectric constants of HSQ films after different X-ray exposure and with and without furnace annealing. Although the dielectric constant of X-ray exposed HSQ films without furnace annealing is higher than that of furnace-cured one, it is obvious that the dielectric constant of X-ray exposed HSQ films with furnace annealing is decreased and close to the furnace-cured one.

Figure 5 shows the leakage current density obtained for HSQ films exposed to X-ray of

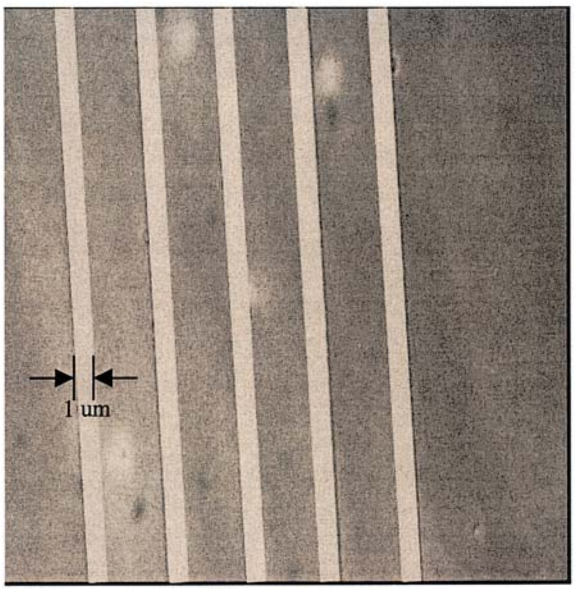

Fig. 3: The optical image of HSQ film after X-ray exposure followed by the development with HSQ solvent.

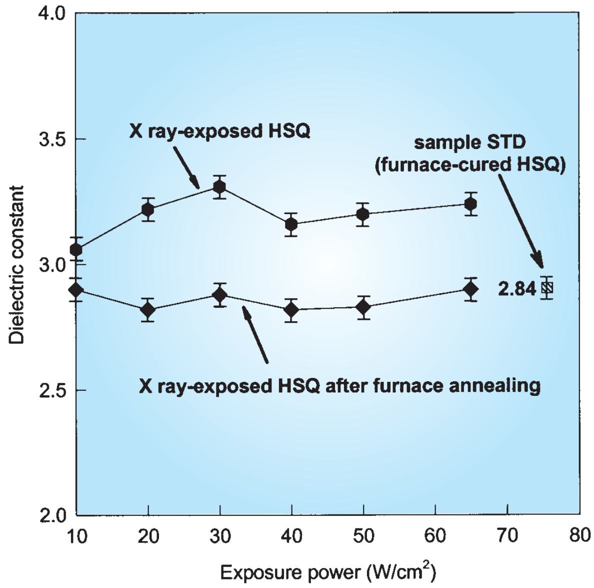

Fig. 4: Comparison of dielectric constant for HSQ's exposed to X-ray of different dosage and subjected to different annealing conditions.

different dosages but furnace-annealed in the same way of 400 ℃ for 1 hour. It is found that the leakage current density of the X-ray exposed films after furnace annealing is close to that of the conventional furnace-curing HSQ. This suggests that X-ray direct exposure combined with the thermal annealing can be extended to simplify the fabrication of the Cu damascene structure that retains excellent dielectric properties of low-k HSQ film.

In summary, the X-ray direct patterning on low-k HSQ as inter-metal dielectric (IMD) has been investigated. In order to avoid the dielectric degradation of low-k HSQ during O_2 plasma ashing process, we proposed a novel X-ray direct patterning on the HSQ film to avoid the damage of photoresist removal process. The X-ray exposure can effectively cure HSQ film to make the cage-like bonds transform to network bonds. Then the unexposed part of HSQ film can be developed by HSQ solvent. In addition, the low-k dielectric characteristics of X-ray exposed HSQ films can be enhanced by a thermal annealing process. From this study, this method can also be applied to manufacture multilevel interconnects of the next generation, that contain numerous nano-sized features.

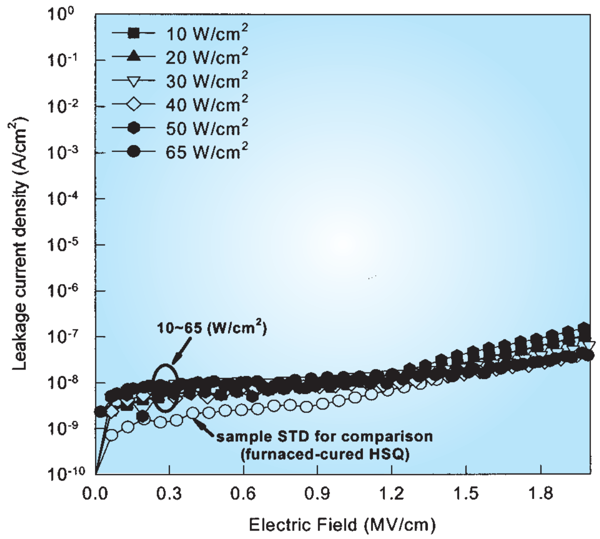

Fig. 5: The leakage current density for HSQ films exposed to X-ray of different dosage but annealed in the same condition of 400 ˚C for 1 hour.

Beamline:

19A1 X-ray Lithography beamline

Experimental Station:

Scanning exposure chamber

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