The Effect of Exposure Mode on Feature Resolution and Film Thickness for Thick (>10 µm) BCB

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KEYWORDS: BCB, ILD, MMIC, GAAS, GAN

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ABSTRACT

Feature resolution in BCB is compared for hard contact and proximity exposure modes. It is found that the proximity exposure mode yields better resolution. This indicates that the limiting factor for critical feature size resolution is something other than film thickness. In addition, it is found that film loss during develop and cure is greater for wafers exposed using proximity. This effect is greatly exaggerated when the density of BCB features on the wafer is low. The density of BCB features also impacts the film loss during the plasma descum step. By taking all of these factors into consideration the desired film thickness and process uniformity is maintained.

INTRODUCTION

Benzocyclobutene (BCB) is a low-k, spin-on dielectric with applications in GaAs and GaN MMIC processing. This dielectric can be used as a scratch protection layer, an inter-level dielectric (ILD) layer for additional metal levels, and for the fabrication of high performance passive components such as high-Q inductors, low-loss balun structures, and low-loss transmission lines.[1] Because the BCB thickness impacts the performance of the passive components (through parasitic capacitance) and the coupling of the baluns, a thick (10-15µm) film is desirable. However, thick photo definable BCB poses several process challenges related to thickness uniformity, feature resolution, pattern density variation, continuity of through-BCB metal connections, and surface topology.[2,3] In this paper, the results of experiments correlating feature resolution and film thickness to the exposure mode (contact versus proximity) are presented.

Although etchable BCB is commercially available, at NGES we employ a process using photo-definable BCB. An etchable variety requires etching of the BCB over critical device active areas which could reduce device performance. With the photo-definable process, BCB is removed from the devices via optical exposure and developing.

BCB PROCESS FLOW

A typical photo definable BCB process flow includes spinning and baking the BCB film, exposing the film with a contact aligner or stepper, and developing the pattern. The film must be cured for polymerization followed by a plasma descum step to remove any developer and/or BCB film residue from the opened areas. The thickness of the film decreases after develop, cure, and plasma descum.[4]

This process flow is outlined in Figure 1. Due to the time sensitive nature of the process, the develop step may be preceded by either an end point monitor wafer (to determine the proper develop time) or a pre-develop bake of the wafers (to re-set the chemistry and ensure a consistent develop time).

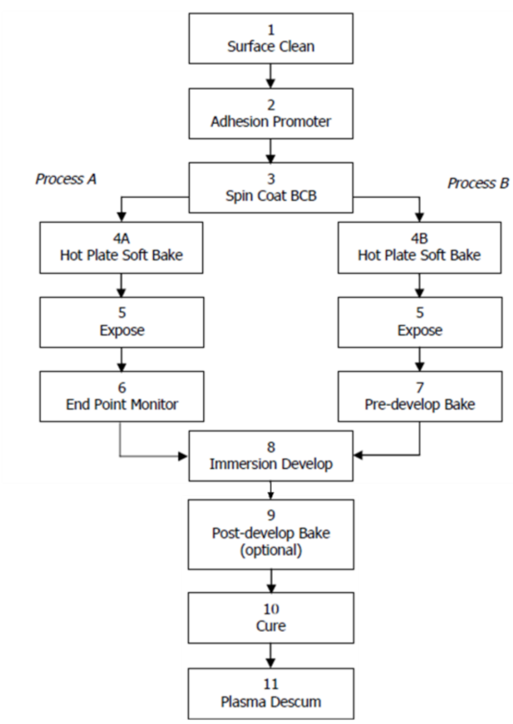

Figure 1. Photo definable BCB process flow. (From Dow Chemical product literature)

At NGES the process is monitored at three points: the spin speed is verified by spinning BCB onto a test piece and measuring its thickness via ellipsometry, and the BCB thickness is measured on product wafers after cure and after plasma descum using a profilometer.

FEATURE RESOLUTION AND EXPOSURE MODE

In order to optimize the minimum feature size using a contact aligner for standard photo-resists, hard contact exposure is typically preferred over proximity exposure mode. In this work, experiments were conducted to compare these two exposure modes for thick BCB.

In order to evaluate and compare the feature resolution of the two modes, a critical-dimension scanning electron microscope (CDSEM) was used to capture an image of a feature in the BCB for every reticle on a wafer. These images (50 µm x 50 µm) were then assembled into a wafer map to highlight patterns across the wafers. A typical result from hard contact can be seen in Figure 2 where, contrary to expectations, the resolution is poor across most of the wafer. This is in contrast to Figure 3 which shows much better resolution across the wafers exposed using the proximity mode. In both cases the BCB was opened to a layer of thick plated metal.

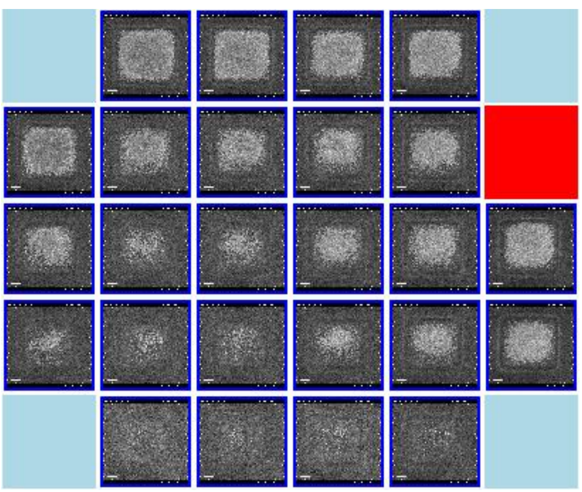

Figure 2. CDSEM wafer map of BCB openings formed using hard contact. Features were 50µm x 50µm on the mask. This result was typical although not universal.

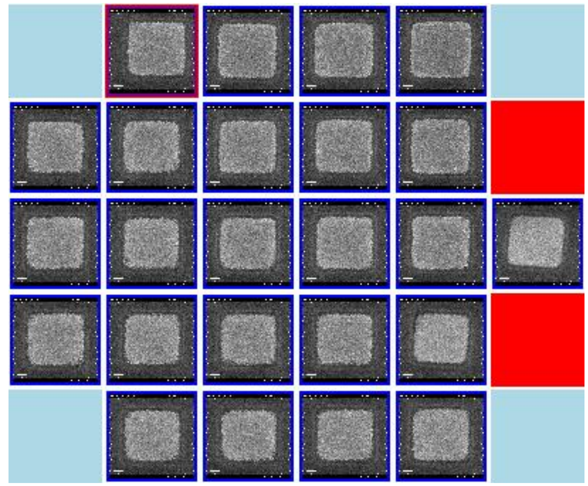

Figure 3. CDSEM wafer map of BCB openings formed using proximity exposure. This type of result was observed without exception.

CDSEM images were also captured for openings to evaporated metal and to the substrate. This was done in order to compare the resolution in areas where the BCB is expected to be thickest (openings to substrate) versus thinnest (openings to plated metal). This thickness variation is illustrated in Figure 4. The best resolution would typically be expected for the regions of thinnest BCB, i.e. for openings to plated metal. Experimental results demonstrate the opposite tendency, as shown in Figures 5 and 6 where the openings to the substrate exhibited superior resolution than those to plated metal. Both sets of images were taken from the same wafer.

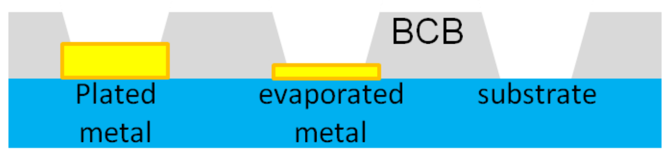

Figure 4. Due to its planarizing tendencies, the BCB thickness depends on the thickness of the local topology over which it is opened.

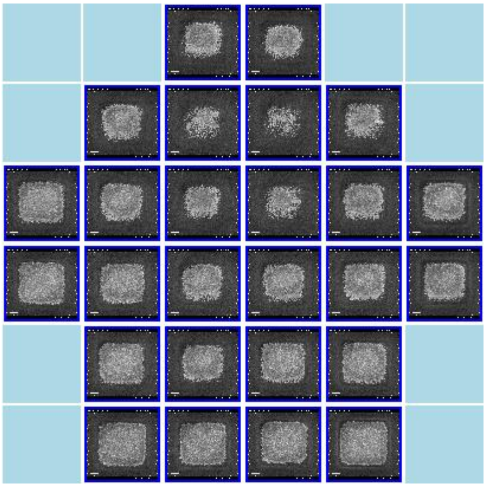

Figure 5. BCB openings to plated metal. Exposed using hard contact.

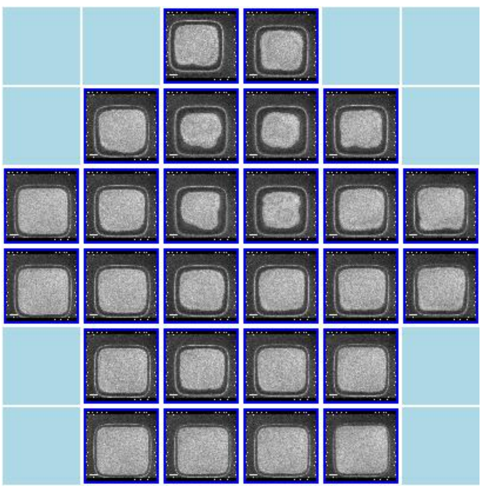

Figure 6. BCB openings to the substrate. Exposed using hard contact. Due to the thicker layer of BCB it would normally be expected that these features would be less well resolved than the openings to plated metal.

These results indicate that the film thickness is not the limiting factor in the ability to resolve features. Further work is needed to pinpoint the particular feature of hard contact which leads to poor resolution if it is to be a viable option for BCB processing.

FILM THICKNESS AND EXPOSURE MODE

One concern regarding a manufacturable BCB process is the amount of film loss during processing. It is necessary that the desired final thickness is consistently achieved, thus film loss during develop, cure, and descum must be tracked. During the course of the exposure mode experiments BCB thickness data was also obtained. It was found that the film loss during develop and cure was dependent on the exposure mode with approximately 1 µm greater loss experienced for the proximity exposed wafers compared to those exposed with hard contact, as seen in Figure 7.

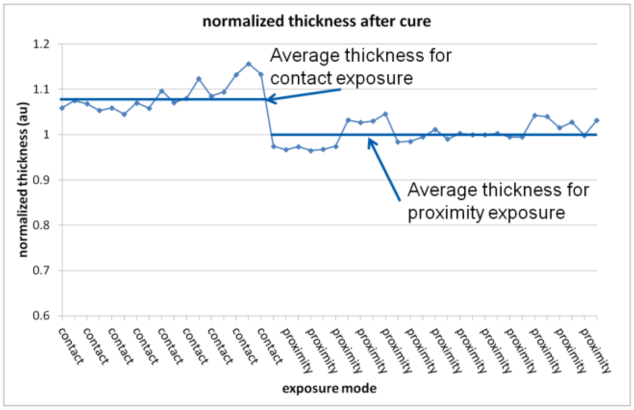

Figure 7. Because of greater film loss, BCB thickness after develop and cure is less for wafers exposed using proximity compared to those exposed using hard contact.

This effect is exaggerated when the density of BCB left on the wafer after develop is low, i.e. the mask used to expose the wafers is mostly opaque, and when the exposure dose is low. Figure 8 summarizes the results of a DOE in which both the mask density and exposure dose was varied in a low/high fashion for wafers exposed using the proximity mode. The film loss during develop and cure was as much as 35% greater for the wafers exposed with either a low density mask or low exposure dose.

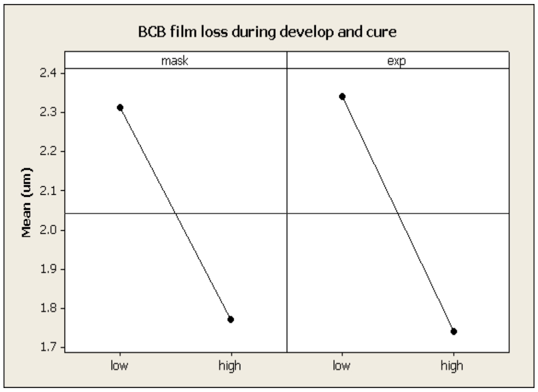

Figure 8. Average thickness loss during develop and cure as a function of mask density and exposure dose.

MASK DENSITY AND FILM LOSS DURING DESCUM

The final step of the BCB process is a plasma descum to remove organic residues including BCB residue from the developed areas. This step causes an additional loss in the film thickness. It was found that the thickness loss was dependent on mask density in much the same way as the thickness loss during develop and cure. For very low mask densities there is a risk that the film loss could reach unacceptable levels, thus experiments were done to quantify the mask densities at which this risk is realized and determine ways to mitigate the risk.

The experiment consisted of running wafers using two different mask sets through the BCB process. Both mask sets had relatively low density of features on the BCB level (15% and 27%). For the plasma descum step the wafers were run through a Reactive Ion Etching tool (RIE) with the BCB thickness measured before and after etching. Table I below details the number of patterned and unpatterned (i.e. fully covered with BCB) wafers in each run. The total number of wafers was fixed at 4 in order to fill the etch chamber for each run. This was done so that the loading effects from both mask density ("local" BCB density) and ratio of patterned to unpatterned wafers ("global" BCB density) could be investigated. Each set of runs was performed for both mask sets.

TABLE I
EXPERIMENTAL DETAILS OF LOADING EFFECTS INVESTIGATION

run	Number of patterned wafers	Number of unpatterned wafers	Total number of wafers
1	1	3	4
2	2	2	4
3	3	1	4
4	4	0	4

Figure 9 is a plot of BCB thickness change versus the number of unpatterned wafers and indicates that the film loss decreases as the number of unpatterned wafers (test pieces) in the chamber is increased. This can be employed to limit the film loss to acceptable levels. For mask densities below a critical value, loading effects do not reduce the film loss to acceptable values. In these cases alternate descum processes must be employed.

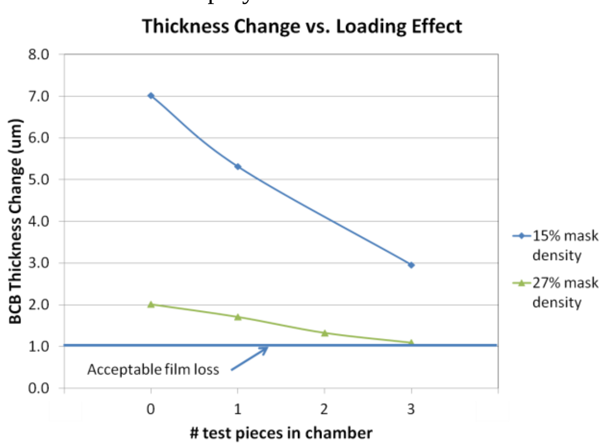

Figure 9. BCB thickness loss during plasma descum for two low density masks versus chamber loading effects.

CONCLUSIONS

Experiments were conducted to investigate the effect of exposure mode on feature resolution in thick BCB films. It was found that hard contact yielded inferior resolution than proximity modes, contrary to what is typically found for optical photoresists. It was also found that hard contact exposures led to less film loss during develop and cure. For wafers exposed with proximity this film loss was greatly influenced by both the density of BCB features on the mask and the exposure dose used. In order to leverage the benefits that hard contact brings with regards to film loss, further work must be done to determine the root cause of its inferior resolution.

Experiments were also conducted to quantify the effect of mask densities and etch chamber loading effects on film loss during plasma descum of the wafers. It was determined that a minimum mask density exists below which no amount of loading effects will prevent an unacceptable amount of film loss.

ACKNOWLEDGEMENTS

The authors would like to thank the GaAs/GaN processing team for their tireless efforts to process and measure the wafers used for this work.

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[2] J. Brown, A. Zhou, J. Campbell, A. Ketterson, *"Optimization and Characterization of a Photo Definable BCB for HV3S and HVHBT Technologies"*, 2011 CS MANTECH Technical Digest, pp. 139-142, May 2011

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[4] Dow Chemical Product Literature

Acronyms
BCB: Benzocyclobutene
GaAs: Gallium Arsenide
GaN: Gallium Nitride
MMIC: Monolithic Microwave Integrated Circuit
NGES: Northrop Grumman Electronic Systems
DOE: Design of experiment
RIE: Reactive Ion Etch