Minimizing Stress in Cu/Polyimide Processes for Large Format MCM Manufacturing

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Abstract

For large format Multichip Module (MCM) manufacturing, mechanical stress in deposited films is a major processing and reliability concern. As substrate dimensions grow beyond 200 mm, warpage induced by film stress can create unacceptable run-in/out levels, requiring less efficient and more expensive lithographic approaches. Residual stress between dissimilar materials/layers can have a dramatic effect on the overall yield and reliability of MCMs through adhesion failure and cracking. Current MCM-D structure is based on the use of photo-imageable polyimide dielectrics and copper interconnects, and existing processes for both of these materials induce fairly significant levels of residual stress. For photo-imageable polyimides, electron-beam (EB) curing is being developed as an alternative to standard thermal/UV processing. In parallel, copper electroplating is being implemented as low stress alternative to DC sputtering. For EB curing, experiments involving changes in dose, beam current, and substrate temperature (during exposure) were performed. EB curing was demonstrated as a reduced stress method for polyimide cure, with maximum improvements seen for cure cycles at temperatures < 200°C. For copper metallization, electroplating was shown to significantly reduce stress levels in deposited films. The effect of changes in seed layer thickness on final properties was investigated, and the mutual compatibility of EB curing and CU electroplating was demonstrated. Predictions of the effect of the improved processes on the warpage of a substrate with a deposited five layer MCM are presented. An appendix is included to provide relations between substrate warpage and depth-of-focus, allowing one to calculate the results of film stress on lithography.

Key words:
Electron-beam, Curing, Electroplating, Polyimide, Copper, Interconnect, and MCM-D.

1. Introduction and Background

For large format Multichip Module (MCM) manufacturing, mechanical stress in deposited films is a major engineering concern. These stresses can warp substrates, especially 600 mm x 600 mm substrates (target substrate size of the MCM-D Consortium, of which Boeing is a member) causing processing problems during manufacture. Metals and dielectrics employed in MCM-D process have coefficients of thermal expansion (CTE) which differ appreciably from that of substrate materials, sometimes by an order of magnitude, which leads to stress generation for any processes involving temperature excursions. Residual stresses can cause yield loss, premature failures, and otherwise impact MCM reliability through a number of mechanisms. When stress levels exceed film strengths, cracking or interfacial failure can result. High stresses for metal films deposited over polyimide have been found to cause plastic deformation of the dielectric layer.1 Passivation cracks can cause delayed failure due to corrosion, or metal cracks can cause early onset failures by electromigration. Failure modes that occur under cyclic fatigue

Primary effects of film stress (and thus substrate deformity) on processing come from robot handling problems and lithographic concerns. For example, bow values > ~70 microns on a 125 mm Silicon wafer leads to handling errors in an SVG 600 Micralign system. Also, from a lithography perspective, warped substrates lead to the need for large Depth of Focus (DOF), which in turn, impacts linewidth resolution. The SVG system has a
depth of focus of 12 microns for a minimum feature size of 1.25 micron, and when processing a wafer with a 70 micron bow, the minimum printable feature size grows to nearly 8 microns (using 436 nm wavelength illumination and optical constants $K_1 = 1, K_2 = 0.5$; see appendix, equation (1)). For large format processing, substrate warpage problems are magnified. In a Model 302 Large Area Scanning Projection System (Tamarack, Scientific, Anaheim, CA), 600 mm x 600 mm substrates can be exposed with one focus/alignment operation. Lithography performance specifications for this system include: at NA= 0.07, res=6.2 μm, DOF=89 μm; at NA=0.14, res=3.2 μm, DOF =22 μm. It can be shown (see appendix) that the stresses generated by buildup of MCM-D film layers can distort a substrate to the point where significant DOF is required for imaging. As substrate dimensions grow beyond 200mm, warpage induced by film stress can also create unacceptable run-in/out levels for lithography equipment which use full-field imaging, perhaps forcing the use of less efficient and more expensive lithographic approaches (such as step-and-scan).

Boeing’s current MCM-D structure is based on the use of photoimageable polyimide dielectrics and copper interconnects, and existing processes for both of these materials induce fairly significant levels of residual stress. For sputtered metal film, internal compressive stresses are often observed when the films are deposited at low substrate temperatures. Boeing uses a negative-acting photoimageable pre-imidized polyimide for MCM fabrication. This material develops tensile stress during thermal processing (softbake and cure). Stress generation in cured films is driven by the difference in CTE between the film and the substrate, in conjunction with the elastic modulus of the film. Anisotropic thermal expansion is driven by the difference in CTE between the film and the substrate, in conjunction with the elastic modulus of the film. As substrate dimensions grow beyond 200mm, warpage induced by film stress can also create unacceptable run-in/out levels for lithography equipment which use full-field imaging, perhaps forcing the use of less efficient and more expensive lithographic approaches (such as step-and-scan).

Thermal Analysis of a Power Amplifier Module with Experimental Calibration

2. Technical Approach

A two-pronged approach was taken to reducing stress levels in MCMs, aiming at both conductor and dielectric layers. To reduce stress in the conductor layers (and eliminate processing problems as described above), electroplating has been investigated as an alternative process to sputtering. The tensile stress magnitude in electroplated copper is two to three times less than that in evaporated deposit, due to improved structural order in electroplated coatings. In order to reduce stresses in cured dielectric layers, it was decided to investigate electron-beam (EB) curing as an alternate to thermal processing. EB processing has been well established as a process for curing thin polymer coatings and stabilizing photoresists. It works by breaking bonds in the polymer structure, some of which can then reform as crosslinks between polymer chains. The crosslinking process increases the molecular weight distribution of the polymer, and is accompanied by the formation of an insoluble gel and an increase in glass transition temperature. Since this process does not require increased temperatures, it can potentially cure polymers without the generation of intrinsic stress due to CTE mismatch.

All wafers used in these studies were 125 mm silicon, covered with a 2500Å coating of thermally grown oxide. For wafers requiring dielectric, an adhesion promoter ($\gamma$-APS) was applied prior to spin coating of the polyimide. The polyimide is spin coated and softbaked (3 minutes hotplate bake @ 100°C and 1 hour N$_2$ oven bake @ 160°C). UV exposures were performed in an SVG Micralign with a broadband source. In the standard cure process, the layer is given an additional UV flood-expose followed by a thermal cure (2 hours @ 200°C followed by 30 minutes at 350°C is recommended by the manufacturer) in a vacuum oven. All thermal cures were performed in an Elnik Systems (Fairfield, New Jersey) model E-1333 infrared heated vacuum oven at a pressure of $<10^{-4}$ Torr. All EB cures were performed in a model ElectronCure 30-200A-T system (Allied-Signal Corp., Electron Vision Group, San Diego, California). The system is based around a large-area EB source, and in addition to exposing substrates to an electron flux, the system can heat substrates from the underside prior to or during exposure.

Copper thin films of the targeted thickness 5µm were deposited using both sputtering and plating techniques. All sputtering was performed in a DC magnetron system manufactured by CVC. 500Å titanium layers were deposited prior to all copper films (nominal 5000Å seed layers as well as full thickness sputtered layers), as an adhesion and a passivation layer. An Argon ion clean step was employed to enhance the adhesion of the titanium to the substrate (either silicon oxide or polyimide), and Argon (3 mTorr) was used as a working gas during sputtering. Electroplating was carried out over sputtered Cu seed layers using a conventional copper-plating bath with automated temperature
control. The plating bath was made up of a sulfuric-acid/copper-
sulfate solution, along with brighteners added to improve grain
structure. Chloride-ion concentration was maintained through
the addition of hydrochloric acid. Anodes were soluble
phosphorised copper balls placed into titanium baskets with
polypropylene filters over the baskets. A low-ripple, ±5% recti-
 fier was used to obtain the desired current density of 3.0 A/ft²
(standard for all plating tests except where stated otherwise). The
plating solution was agitated with air and circulated through a
carbon filter.

All stress measurements were performed in a Flexus F2320
stress measurement system (TENCOR Corp., Sunnyvale, Cali-
fornia). The system uses a laser to determine the curvature of
a wafer, and is capable of heating and cooling wafers according to
prescribed user-defined thermal recipes. When scans are taken
of a wafer’s curvature both before and after deposition of a thin
film, then the system can calculate the stress in the film through
the use of Stone’s equation, modified to account for biaxial
stresses (see appendix). The key assumptions behind the use of
Stone’s equation are that the film thickness is less than 5% of
the thickness of the substrate, and that the film’s modulus does
not greatly exceed that of the substrate. For these tests, 5 micron
layers of copper and polyimide were measured on a 625 micron
thick Silicon wafers, and the biaxial modulus of the silicon (180
GPa) exceeds that of the polyimide (~4 GPa) and is near that of
copper (190 GPa).

3. Polyimide Process Results

The curing process for the pre-imidized polyimide consists of
both chemical (crosslinking) and physical (solvent evaporation)
phenomena. Although the exact chemistry is proprietary, it is
known that the polymer backbone contains segments made from
both 6FDA and BTDA. It is the BTDA moiety that is inherently
photosensitive, providing a cross-linked polymer upon exposure
to UV radiation. Additionally, thermal exposure at temperature
at/above 350°C can be used to effect a light thermal crosslinking.

Figure 1 provides a box plot of measured film stress data for a
variety of thermal cure temperatures. The data at 25°C are mea-
surements for films that have been softbaked (1 hour @ 160°C),
flood-exposed and developed. It can be seen that the film stress
increases with increasing cure temperature, mostly due to addi-
tional solvent loss and the ‘gel collapse’ mechanism described
previously. Weight data taken during various stages in process-
ning show ~2% loss in solvent induced by 250°C curing, and ~
4.5% after 350°C curing (error in data caused by poor scale preci-
sion prevented more in-depth analysis). Thickness measure-
ments taken before and after curing show thickness loss of ~4%
for 250°C curing and ~5% for 350°C curing (thickness measure-
ments were also hampered by precision problems).

Figure 1. Film stress in thermal cured polyimide.

The results of EB cure tests are summarized in Figure 2. All
of these samples were given the standard processing steps up
through and including solvent develop prior to EB exposure (wa-
fers were not given the high dose flood exposure). Test cures
were performed at various electron doses (1000, 1500, 2000, 5000
microCoulombs/cm² of total charge, abbreviated henceforth as
µC), accelerating voltages (14, 20 kilo-electron Volts), and tem-
perature conditions (RT or 250°C). RT means that no active
heating was employed to hold wafer at a pre-determined tem-
perature during cure. Wafer heating occurs during EB exposure
from transfer of kinetic energy of electrons into heating of the
attenuating film. With long exposures, wafers can reach tem-
peratures of 200°C or higher. For example, a 5000 µC exposure
made using a 5 mA beam current took 23 minutes to perform.
At the end of the exposure, the wafer temperature had reached
200°C. For shorter exposures (2000 µC and below), wafer tem-
perature did not generally exceed ~160°C (which is the tempera-
ture of the oven softbake step all wafers are subject to). All EB
cures were performed using a stepped beam current recipe, the
first 250 µC were delivered at 2 mA current, the next at 4 mA,
the remainder at 6 mA, to allow the electron beam to stabilize at
the onset of the cure cycle. Also included in Figure 2 are the
results of the stress tests for thermal cures at 350°C (manufactur-
ers recommended cycle).

Figure 2. Stress in EB cured polyimide.

A few trends are readily apparent from a viewing of the re-
results. First, it can be seen that stress levels are greatly reduced
for the low dose e-beam cures without active heating. At the
1000 µC dose, stresses were ~25 MPa, rising to above 35 MPa
for the 5000 µC dose wafer. This is due to the effects of the flux induced heating of the wafer; with increased heating and increased solvent loss and thus more stress. Additionally, it is seen that the three cure conditions where the wafers were brought up to and held at 250°C gave similar stress level results (35.5-38 MPa). Finally, no perceptible difference is seen in the stress levels between wafers, given the same dose but at different accelerating voltages. This is expected, as accelerating voltage changes within this range would only affect the flux penetration depth. Note that the spread of error bars in Figure 2 can be somewhat deceiving, these bars are due to smaller sample counts for the EB cure conditions.

In addition to getting stress measurements in cured films at room temperature, a series of stress versus temperature measurements were performed on thermal and EB cured wafers using the hotplate heating features of the Flexus system. Wafers were heated to 250°C at 10°C/minute rise rate, then cooled back to RT at <10°C/minute. The thermally cured wafers (Figure 3) showed the expected linear stress-temp response, however the wafers given EB cures without temperature assist (Figure 4) showed different slopes for the heatup cycle compared to cooldown. This indicates that additional solvent loss (with associated stress increase) occurred during the thermal cycle. Upon additional cycling of EB wafers, the stress/temp curves showed similar linear response to the thermally cured wafers (Figure 3).

Based on these results, questions arose as to whether EB cured polyimide coatings could withstand subsequent metallization and multilayer processing. A number of tests were performed on films cured without heat assist at 1000, 1500 and 2000 µC doses at 14 KeV, along with baseline thermal cured films. One set of EB cured films was sputtered with a 5000Å seed layer of copper using previously described procedures. Inspections of the deposited copper films showed similar good quality results, with good adhesion and no evidence of delamination between copper and polyimide. These wafers were placed in an oven with a (mostly) Nitrogen atmosphere at 250°C for 15 minutes, then, reinspected. The wafers showed high levels of surface oxidation of the copper (due to the presence of small amounts of oxygen in the oven), but still no signs of delamination or distortion of the copper. Other polyimide coated wafers, given the same EB cures, were coated with a second layer of polyimide. The second layer was then softbaked, exposed, and developed. No evidence of the distortion or dissolution was found, providing further evidence that some chemical transformation (such as cross-linking) had occurred due to the EB exposure. EB curing has been found adequate for most MCM applications involving this polyimide.

4. Copper Process Results

The results of stress measurements taken of copper films sputtered or plated (over 5000Å sputtered seed layer) over bare oxidized wafers are presented in Figure 5. Also included are the results for films sputtered or plated over thermally or EB cured polyimide. Full thickness sputtered films were not deposited over EB cured polyimide. As can be seen, plated films have greatly reduced stress (~90 MPa) when compared to fully sputtered films (~190 MPa). In fact, recent tests at Boeing have shown that by reducing current density to 1.5 A/ft^2, the stress level can be reduced to ~50 MPa for 5 micron films. Clearly, this result is at the expense of reduced throughput. Also, stresses are lower when deposited over polyimide as compared to films deposited over oxide alone, although the level of stress reduction is much less for the plated case. This behavior has been investigated previously, and had been attributed to elastic/plastic deformation of the polyimide. No significant difference is seen between the plated stress over thermal cured versus EB cured polyimide.

Figure 3. Stress vs. temperature, thermally cured polyimide (380°C for 10 min.).

Figure 4. Stress vs. temperature, EB cured polyimide (1000 mC cm^2).

Figure 5. Copper stress vs. deposition method.
Figure 6 shows the total stress, seed layer thickness effect in the copper plated films. The first set of box and whisker plots is the total film stress (sputtered seed layer plus plated remainder), the second set is for seed layer stress only (1000, 5000, or 7000Å) and the final set is for the plated portion only. There is an inverse dependence of the seed layer thickness on stress in copper films plated on polyimide (both thermal and e-beam results are included into the 5000Å case). The 1000Å sputtered seed layers have very high stress, which translates into higher stress in the overall composite film. As sputtered seed thickness increases, the stress levels approach that seen in the full thickness sputtered layers (~120-140 MPa). The final group of plots (plated thickness only) seems to indicate that the plated material deposited over the high stress 1000Å seed also is of a higher stress than the films plated over thicker seeds. The seed layer likely has an influence on the crystallographic state (grain size and texture) of the plated film, and stress may be higher in thinner underlayers due to more obstacles for material flow by smaller grains.

Figure 6. Effect of seed thickness on stress.

To investigate the effects of temperature cycling on the stress state of plated versus sputtered copper films, wafers consisting of ~5 micron films on bare oxide were subjected to 250°C exposure in the Flexus system. The results of the stress versus temperature measurements are provided in Figure 7. As shown, the stress state of both films is initially tensile, but switches to compressive upon heating to 250°C, due to CTE mismatch between the film and the substrate. The plated film undergoes a higher compressive stress at temperature and responds to the stress by relaxing. Mechanisms for compressive stress relaxation include hillock growth and grain regrowth. Upon continued heating, the stress states switch back from compressive to tensile, indicating the continuation of grain growth processes (and densification), in both films. Note that the plated copper shows a greater increase in tensile stress after 40 minutes exposure than the fully sputtered film, providing some evidence of differences in the microstructure between the two films.

Figure 7. Stress vs. temperature – copper on oxide wafers.

Another set of experiments (Figure 8) was performed to check the change in stress of the copper layer with temperature cycling. Sputtered and plated wafers were given repeated exposure to either 90 minutes @160°C in Nitrogen (nominal temperature exposure of wafers processed using EB cures without active heating) or the polyimide thermal cure cycle. The plated wafers increased in stress after one cycle and maintained a level of 150-170 MPa, as did the sputtered wafer exposed to the 200°C/350°C cycles. What was unexpected was the dramatic increase in stress in the sputtered wafers exposed to 160°C cycles, a behavior not seen to the same extent for the plated wafer. Figure 7 indicates that plated film shows a greater tendency to build in tensile stress with 160°C temperature exposure, but this finding does not appear consistent with the results of Figure 8, which indicate a greater stress change in the sputtered films. The mechanisms for stress generation and relief are complex, and additional work is needed to understand these results.

Figure 8. Copper stress after repeated temperature exposures.

Additional experiments were performed on wafers with copper films deposited over cured polyimide. Figure 9 shows stress versus temperature data for sputtered and plated films deposited...
on baseline thermal/UV cured polyimide and for a plated film deposited over EB cured polyimide. Behavior of these wafers is similar to that of the wafers in Figure 7, as the temperature rises the stress states go from tensile to compressive. Once ∼100 MPa compressive stress is reached, then stress relaxation begins to occur. Note the sputtered film wafer showed a moderate rise in stress after each cycle. Unfortunately, the cycles only cooled to ∼120°C, so it is difficult to correlate the stress data for these films (deposited over polyimide) with the results of Figure 8 (deposited over bare oxide). The plated/EB test was discontinued ∼80 minutes into the experiment after some film disbonding caused the measurement problems. Similar problems occurred with the sputtered/thermal-cured wafer after 1 ½ temperature cycles. The plated/thermal-cured wafer survived three temperature cycles before failure. Attempts were made to take another set of wafers to 350°C, but full disbonding occurred for both thermally cured and EB cured wafers. This disbonding is not normally seen in patterned metallizations over polyimide, and it is likely due to the trapping of solvent diffusion.

In Reference9, equations to be used to estimate the effects of depositiing a stressed film onto a substrate are found. Equating the bow in a substrate as the Depth of Focus (DOF) needed to pattern the substrate, it can be shown (see appendix) that the DOF required to image a large format glass substrate is ∼545 microns. Performing the same calculations but substituting a plated film (σ = 90 MPa) for a sputtered film given a DOF needed of only ∼230 microns, nearly a 2:1 improvement. Similar calculations can also be performed to estimate the effects of changing the polyimide cure from a thermal/UV to an EB process. For a five layer MCM (25 microns total polyimide), a cure stress of 40 MPa leads to a DOF needed of ∼520 microns, while if the stress is reduced to 25 MPa, then the DOF is reduced to 325 microns. Also, while copper stress has somewhat temporary effects on processing (wafer bow was reduced ∼50% after metal etch, depending on the amount of copper coverage in the completed layer), polyimide stress remains active on the substrate and its effects are cumulative with each successive layer.

5. Conclusions

In MCMs, the authors have been able to significantly reduce tensile stress levels by applying alternative processing techniques. Electron-beam curing of photosensitive polyimide and electroplate deposition of copper have been investigated as alternatives for thermally cured polyimide and sputtered copper. The findings presented in this work indicate that warpage values can be reduced significantly when these low stress processes are implemented. EB curing was demonstrated as a method for providing a ∼40% reduction in these stresses. Adequate solvent resistance was demonstrated, along with the ability to metallize, and etch over EB cured polyimide. For plated copper, a similar stress reduction was observed compared to sputtered copper, and there was no significant difference observed for films plated over EB or thermally cured polyimide. Additionally, an increase in (sputtered) seed layer thickness reduces the stress in the electroplated deposit and in the overall (sputtered/plated) composite layer.

Future directions for this work include the implementation of these processes into multilayer MCM manufacture, and the gauging of the effects of these new processes on long term device reliability. Questions still remain as to whether the gains in stress reduction during manufacture can be maintained through the assembly process and over the life of the product. Additionally, future work should focus on the applicability of the EB cure process for other types of dielectric polymers. The process may open up new avenues in dielectrics by enabling the use of polymers that have not previously been employed since they were not formulated to crosslink in a traditional thermal cure process.

Acknowledgments

This work was supported by DARPA under Technology Reinvestment Project #MDA972-94-3-0035, with thanks to Program Manager, Dr. James Murphy. Thanks are extended to J. Nielsen L. Branson, C. Littlejohn, K. Coates, and R. Vandegrift of Boeing for equipment support. Thanks also to P. Kohl, S-A Bidstrup-Allen, K. Farnsworth and R. Manepalli of the Georgia Institute of Technology for many stimulating discussions concerning polyimide processing and EB curing.

References


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Appendix

Linewidth and depth of focus are interrelated by the relationship

\[
\text{Depth of Focus} = \frac{K_2}{K_1} \times \text{linewidth}^2
\]

where \(K_1\) and \(K_2\) are optical constants and \(l\) is exposure wavelength.

Stoney’s equation, modified for the biaxial stress state, is of the form

\[
\text{Linewidth} = \frac{\lambda}{K_1} \times \text{Depth of Focus} \times \frac{1}{K_2}
\]

where \(K_1\), \(K_2\), and \(\lambda\) are constants.

\(\text{Linewidth} \times \text{Depth of Focus} = \frac{\lambda}{K_1 K_2} \times \text{Depth of Focus}^2
\]

\[
\text{Linewidth} = \frac{\lambda}{K_1 K_2} \times \text{Depth of Focus}^2
\]

\[
\text{Linewidth} = \lambda \times \text{Depth of Focus}^2
\]

where \(\lambda\) is wavelength and \(K_1\) and \(K_2\) are optical constants.
\[
\sigma = \frac{Eh^2}{6(1-\nu)Rt}
\]

which provides thin film stress as a function of substrate warpage. This can be manipulated to give the change in radius in response to the deposition of a stressy film in the form,

\[
\Delta R = \frac{Eh^2}{6(1-\nu)\sigma t}
\]

where \(E/(1-h)\) is the biaxial Elastic Modulus, \(\sigma\) is the thin film stress, \(h\) and \(t\) are the substrate, and the film thicknesses, respectively. The change in radius is related to the radius before \(R_1\) and after deposition \(R_2\) by the following,

\[
\Delta R = \frac{R_1R_2}{R_1 - R_2}
\]

The radius of a warped substrate is related to the required DOF needed to image the full field by the relation\(^9\),

\[
R_2 = \frac{c^2 + 4DOF^2}{8DOF}
\]

Using equations (3), (4), and (5) along with typical values for a single sputtered copper metallization on a glass substrate (see Table below), one can calculate a warpage level such that a minimum of \(~545\) microns DOF would be needed for imaging. Alternatively, this warpage would need to be removed during exposure (for example using vacuum chucks) in order to avoid impact to linewidth resolution.

<table>
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<th>Value</th>
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<tr>
<td>Max span of exposure area (c)</td>
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