An Investigation of the Properties of Photosensitive Polyimide Films

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Modern package designs generate a large amount of stress on the die which can be controlled using a thick film of polyimide over the passivation layer. Polyimide film thicknesses in excess of twenty microns at exposure are becoming common for very thin packages. The standard polyimide lithographic process frequently utilizes a trilayer film consisting of an adhesion layer, a polyimide film, and photoresist. A major advance in polyimide technology occurred with the introduction of photosensitive polyimide materials. These materials reduce the total number of process steps in the polyimide process. They also offer the opportunity to combine the passivation and polyimide lithography steps into one process level resulting in significant process simplification and manufacturing cost reduction. Consequently, there is a rapid increase in the use of photosensitive polyimides in the semiconductor industry.

There are a number of important issues associated with photosensitive polyimide processing. Because most photosensitive polyimides are negative tone, residual film formation has a major impact on resolution and the usable process window. The high exposure doses required for thicker polyimide films exacerbates the residual film problem. Also, resolving small features such as fuse windows in DRAMs is frequently required in thick photosensitive polyimide layers. These small features result in polyimide height-to-linewidth aspect ratios that are comparable to many photoresist applications. Because of these requirements, photosensitive polyimide applications could benefit from detailed process characterization to enhance resolution and increase process latitude. Unfortunately, there is scant literature pertaining to lithographic performance and lithographic process modeling for photosensitive polyimide films.

An extension of basic photoresist characterization techniques for thin films can be applied to thick photosensitive polyimide processes. The develop rate characteristics and lithographic performance for several commercial photosensitive polyimide products were studied at a thickness of 12 microns. Cross sectional SEM analysis, Bossung plots, and film retention plots are used to establish relative lithographic capabilities. These experimental results are used to study the effects of polyimide physical and chemical properties on lithographic performance.
1.0 INTRODUCTION

Photosensitive polyimides are becoming an accepted group of materials within the semiconductor industry. The dominant application of photosensitive polyimides is as a stress-buffer coating for devices in thin and ultra-thin packages [1]. Particular devices of concern include large-die devices packaged in plastic molding compounds, exemplified by dynamic random access memory (DRAM) components. These die are subject to significant amounts of stress, primarily resulting from differing coefficients of thermal expansion of the die and packaging compounds [2]. These stresses may lead to cracking of the package or the protective passivation layer, allowing the introduction of contaminants such as moisture and ionic particles. Imparted stress may also lead to metal or wire-bond deformation, possibly altering device parameters. In both cases device reliability and yield may be severely degraded. To reduce stress imparted to the die, a relatively thick layer of polyimide is applied over passivation as shown in Figure 1. In addition, the polyimide layer serves to protect the die from the coarse composition of the molding compound as shown in Figure 2.

Conventional, or non-photosensitive polyimides have been extensively used as stress buffer coatings but have process limitations. Historically, polyimide was applied after wire bonding as part of the packaging process. The material was dispensed on a wire-bonded die and allowed to flow over the surface of the die and around the wire-bonds. However, this process has been moved to the wafer fabrication area to improve process control and accommodate lead-on-chip (LOC) package designs. During wafer fabrication, a layer of polyimide is applied on the wafer using a spin-dispense technique similar to that of photoresist. A layer of photoresist is then applied on top of the polyimide and exposed using a photolithography tool. The photoresist is then developed which exposes the areas of the polyimide to be removed, which is usually accomplished by a wet-etch process. This non-photosensitive wafer fabrication approach has a significant level of process complexity, as well as limited resolution and poor sidewall profile quality resulting from the isotropic polyimide etch process.

To address the process complexity and limited performance, polyimide suppliers have recently introduced photosensitive polyimide products. These materials may be directly exposed using a photolithography tool which simplifies the process. It also provides significant advantages of superior resolution and improved sidewall profiles [3]. Because of the improved sidewall profile, the photosensitive polyimide layer can be used as the etch mask for the passivation layer. This allows the elimination of an entire photolithography level in the manufacturing cycle. This process simplification was not previously available with wet etch processes due to the lack of vertical sidewall profiles. Incorporating photosensitive polyimide along with passivation masking results in the process illustrated in Figure 3.

The simplified photosensitive polyimide process decreases costs by eliminating manufacturing processes (particularly a lithography step), decreasing cycle-time through the manufacturing facility, decreasing product handling near the end of the manufacturing cycle (increased yield),
increasing available manufacturing capacity (as a result of process elimination), and reducing material costs (also as a result of process elimination).

The photolithography requirements of a photosensitive polyimide stress buffer level typically pose less stringent resolution and overlay requirements than other lithographic levels. Bonding pads may be on the order of 100 μm square with overlay requirements as large as several microns. However, resolving small features, such as fuse windows in DRAMs, are frequently required in these film layers. These fuse windows may be less than 15 μm square in film thicknesses approaching 30 μm, making the height-to-linewidth aspect ratios comparable to those found in more advanced photoresist applications. In addition, the inherent resolution capabilities of photosensitive polyimides are currently limited, in comparison to those of typical photoresist materials.

Another challenging aspect of photosensitive polyimide photolithography is minimizing residual film formation. Virtually all commercially available photosensitive polyimides are negative tone. In other words, the exposed material will remain on the wafer and become an integral part of the device. Residual film formation on bonding pads or within scribe lanes may lead to electrical resistance issues and decreased product yield. Residual film formation also has a major impact on ultimate resolution and the resulting process latitude. The high exposure doses required for thick polyimide films result in scattered light generated in the photolithography system which exacerbate this residual film problem [4].

Integrated circuits also have maximum topography at the end of the wafer processing cycle which can cause polyimide thickness variation, which reduces the critical dimension (CD) control. This thickness variation increases as a result of the planarization properties of photosensitive polyimide materials. The CD control is also affected by the specific optical properties and develop characteristics. First, bulk absorption effects of the polyimide reduces the effective dose at the bottom of the film. The observed effect is exacerbated by the isotropic wet development process, which produces sloped profiles. An exposure effect that impacts CD control is standing wave phenomena which result from highly reflective films. These factors suggest that the lithographic problems associated with thick polyimide films can be just as challenging as other lithography levels. Clearly, polyimide applications would benefit from process characterization and modeling similar to photoresists used in semiconductor processing.

Photosensitive polyimides currently may be divided into two distinct types based on their chemistry. In the first type, the photosensitive groups are linked to the carboxylic group of the polyimide precursor through ester linkage as shown in Figure 4 [5]. Materials based upon this technology, originally developed and licensed by Siemens, are offered by several companies including Asahi Chemical, DuPont Electronic Materials, and OCG Microelectronic Materials. The second type is based upon an acid-amine ion linkage between the photosensitive groups and the polyimide precursor solution as shown in Figure 5 [5]. This formulation is patented and also marketed by Toray.
The purpose of this work is to experimentally evaluate two commercial polyimides and to compare the resulting industry standard metrics for photoresists. Traditional characterization techniques such as cross-sectional SEM analysis, Bossung plots, and film retention plots are used to establish the relative lithographic performance. The effect of various modeling parameters will then be presented to illustrate how polyimide materials could be improved for thick film applications in the future.

2.0 EXPERIMENTAL METHODS

Two commercially available g-line photosensitive polyimide products were examined for their develop rate behavior, focus/exposure process windows, and sidewall profiles. Both materials are specifically designed for photosensitive polyimide applications in excess of ten microns thickness. One of the polyimide materials is based on the Siemens chemistry (Figure 4) while the other material is based on the Toray chemistry (Figure 5). The two products will be designated as polyimide type A and type B, respectively, for this study.

An Ultratech Titan Wafer Stepper™ was used for all of the polyimide process experiments. The Ultratech stepper is based on the 1x Wynne-Dyson lens design using broadband g and h mercury lines including the wavelength continuum from 390 to 450 nm [6]. This system has a numerical aperture of 0.26 and a partial coherence of 0.6 which makes it well suited for thick photoresist or polyimide applications [7].

Bare silicon wafers of 150 mm diameter were used for this study. No HMDS vapor prime was used on the wafers since it is not an effective adhesion promoter for polyimides. The wafer layout for both polyimides consisted of an 11 by 11 matrix as shown in Figure 6, with field dimensions of 10 mm in both x and y. The small field size was selected to maximize the number of focus and exposure variations that could be placed on a single wafer which minimizes wafer to wafer process variation effects. The focus was varied in the x axis from -7.5 μm to +7.5 μm in 1.5 μm steps. The exposure was varied in the y axis from -25 to +25 percent of nominal exposure in 5 percent steps. The nominal exposure for the type A material is approximately 1500 mJ/cm² and for the type B material is 250 mJ/cm². The large exposure difference between the polyimides suggests that the type A material would have lower lithography throughput than the type B material.

The polyimide coat and softbake processes were performed on a Solitec 5110C system. The dispense procedure for both types of polyimide included a static dispense, constant acceleration for a ten second spread cycle, followed by a final spin speed that was adjusted to achieve a film thickness (T₀) of 12.0 μm. The thickness was measured after prebake for both type A and B materials using a Sloan Dektak 3030 profilometer.

Softbake processing was performed on a Solitec hotplate bake unit. The type A material was baked for three minutes at 70°C with soft contact. The type B material was baked at 80°C for four
minutes and then an additional four minutes at 100°C with soft contact. The five minute longer prebake for the type B material dramatically reduces throughput on the prebake track equipment.

Polyimide development processing was performed using a Solitec spray develop system. The vendor’s recommended developer was used for each product. It is important to note that both of these materials require organic developer chemistries. The type A material had a nominal spray develop time of 14 seconds. The type B material required a more complex eight step spray/puddle develop with a nominal develop time of 13 seconds per spray/puddle step for a total develop time of 104 seconds. The develop times were varied by ±15 percent for both type A and B materials to establish the latitude of the develop process. The large develop time difference between the polyimides suggests that the type A material should have a higher throughput on the developer track equipment than the type B material.

The polyimide critical dimensions (CD) and final film thickness (T) were measured using a KLA 5107 Coherence Probe Microscope [8]. This system can make measurements through an extended focus range for thick photoresist or polyimide features due to a large z direction scan capability. Nominal six micron horizontal dense features were measured over the focus and exposure matrix on each wafer. Included during this measurement scheme were the top and bottom linewidth along with the film thickness. The top of the polyimide lines were measured using a threshold range of 35 - 40 percent to accommodate process variation, and the bottom of the polyimide lines were measured using a 30 percent threshold.

3.0 RESULTS

3.1 Film Retention

The after develop film thickness (T) was measured at zero focus over the ±25 percent range of exposure doses. The film retention curves for the type A polyimide are shown in Figure 7. The three curves correspond to the development times of 14, 12, and 10 seconds. The dose at the transition knee is approximately 1350 mJ/cm² for the 14 second develop time and 1200 mJ/cm² for the 12 and 10 second develop times. The shortest develop time produces the largest film retention which is typical for a negative acting photosensitive material. The thickness loss relative to \( T_0 \) is typical for this material.

The film retention curve for the type B polyimide appears to be a step function which achieves a final film thickness of approximately six microns at a very low exposure dose. The experimental exposure range for the type B polyimide was not low enough to establish the exposure transition knee. In addition, the film retention thickness appeared to be independent of the three develop times. These results suggest that the develop process used in this study was not optimal for the material. In fact, the type B polyimide manufacturer recommends purchasing an especially designed dispense nozzle capable of rapidly dispensing a large volume of developer. The
recommended dispense rate for the type B is six times that of the type A material which suggest that the chemical costs per wafer would be much higher for the type B.

3.2 Focus/Exposure Results

Bossung plots for six micron lines in polyimide type A are shown in Figures 8, 9, and 10 for the 14, 12, and 10 second develop times respectively. All three figures show the classic Bossung pattern with concave and convex curves as a function of exposure. There is no indication of a major offset from nominal focus for these curves. Such focus offsets corresponding to the isofocal point are frequently observed for thick photoresist films [7]. This difference in focus offsets is probably due to the negative photosensitive chemistry of the polyimide materials. The ±10 percent CD control limits are shown in each figure in order to quantify the process latitude. The focus and exposure latitude for each develop time is shown in Table 1. All three develop times give a comparable focus latitude of approximately 12 microns. However, the 14 second develop time provides the best exposure latitude for the type A polyimide.

Bossung plots for six micron lines in polyimide type B are shown in Figures 11 and 12 for the 120 and 104 second develop times respectively. The large amount of scatter in the results masks any convex or concave curvature trends. No figure is shown for the shortest develop time of 88 seconds because the six micron lines did not clear for this case. Figure 11 indicates that all of the CD measurements for the longest develop time are out of the ±10 percent CD limits. These results suggest that the type B polyimide has a very small develop process window in comparison to the type A material. The focus and exposure latitude to maintain ±10 percent CD control for the 104 second develop time is shown in Table 1. The focus latitude of 10 microns and an exposure latitude of 10 percent is substantially less than the best case develop time for the type A polyimide. However, the type B process latitude has the potential to be improved if the manufacturer recommend high speed dispense nozzle is implemented.

3.3 SEM Analysis

Complete SEM analysis was performed to evaluate the sidewall profile quality of six micron line and space patterns for both type A and B polyimides as shown in Figures 13 and 14 respectively. At zero focus the type A polyimide exhibits near vertical wall angles with smooth surfaces. The positive defocus shows a characteristic undercut that is very pronounced at lower doses. This condition is undesirable since it could impact the reliability of the packaging operation. The negative defocus shows substantially less undercut than the positive defocus condition.

The type B polyimide shows dramatically different results. The lines show extreme scalloping of the sidewalls and with minor scalloping across the top of the line. The sidewall angles show a significant amount of slope in comparison to the type A material. Even at zero focus the sidewalls show a larger angle than the type A polyimide. The sidewall angles are particularly poor through focus at the lower doses with a clear “milkbottle” effect at positive defocus conditions.
4.0 CONCLUSIONS

An extension of basic photoresist characterization techniques for thin films has been applied to a thick photosensitive polyimide processes. The develop rate characteristics and lithographic performance for two commercial photosensitive polyimide products were studied. One of the polyimide materials is based on the chemistry developed by Siemens while the other material is based on the Toray chemistry. SEM profile analysis, Bossung plots, and film retention plots were used to establish relative lithographic capabilities.

The two polyimide materials had very different process characteristics. The type A material requires a much larger exposure dose which impacts the throughput on the lithography system. However, the type B material requires a much longer prebake and a longer develop time. As a result, the type B material would require the purchase of more prebake and developer track systems to maintain the same effective throughput as the type A material. In addition, the recommended volume of developer for the type B material is larger than the type A material which increases chemical consumption. All of these factors could have substantial impact on the total cost of the photosensitive polyimide module in a manufacturing environment and must be carefully considered to minimize the total cost of ownership.

The type A polyimide exhibited standard film retention characteristics for a negative photosensitive material. The film retention curve for the type B polyimide appeared to be a step function which indicated that the developer chemistry is probably not optimized for the material. This was also evident in the small develop process latitude that was observed for the type B material.

Bossung plots of both types of polyimide showed that the type A material has a larger focus and exposure latitude than the type B material. The type A material demonstrated 12 microns depth of focus with a 20 percent exposure latitude for six micron lines with ±10 percent CD control limits. In comparison, the type B polyimide exhibited 10 microns depth of focus and 10 percent exposure latitude. However, the process latitude of the type B material has the potential to be improved if the manufacturer recommended high speed dispense nozzle is implemented.

SEM analysis indicates that the type A material had substantially better sidewall angles and line edge roughness. The sidewall profiles indicated different problems for both type of materials at large positive defocus values. This suggests that the focus should be set slightly negative for both type of materials to maintain vertical wall profiles.

These experimental results suggest that physical and chemical properties can have a profound impact on lithographic performance of photosensitive polyimide materials. Simulation and modeling techniques will be used in future studies to further quantify these relationships.
5.0 REFERENCES


**Figure 1**: Cut-away of a wire bonded die with the bonding pads exposed through the polyimide film which is used as a stress buffer coating.

**Figure 2**: Cross section of a CMOS device in a plastic package. Here photosensitive polyimide is used as a stress buffer overcoat between the passivation and the package molding compound.
Figure 3: Comparison of conventional polyimide process and photosensitive polyimide process.

Table 1: Process latitude as a function of polyimide type and developer time for six micron lines with a ±10% process window. These results are based on the bossung plots in figures 8 though 12.
Figure 4: Photosensitive polyimide based on photosensitive group linkage of the polyimide precursor through ester linkage (Siemens chemistry).

Figure 5: Photosensitive polyimide based on acid-amine linkage between the photosensitive groups and a polyimide precursor (Toray chemistry).
Figure 6: Wafer map showing the focus exposure matrix used to characterize the photosensitive polyimide materials. The nominal value for focus and exposure is at the center of the wafer.

Figure 7: Film retention plot for polyimide type A. This shows the polyimide thickness after develop versus exposure dose for spray develop times of 14, 12 and 10 seconds.
Figure 8: Bossung plot for polyimide type A using a 14 second spray development process. The nominal line size is six microns with ± 10% control limits.

Figure 9: Bossung plot for polyimide type A using a 12 second spray development process. The nominal line size is six microns with ± 10% control limits.
**Figure 10:** Bossung plot for polyimide type A using a 10 second spray development process. The nominal line size is six microns with ± 10% control limits.

**Figure 11:** Bossung plot for polyimide type B using an eight step puddle/spray development process for 120 seconds. The nominal line size is six microns with ± 10% control limits.
Figure 12: Bossung plot for polyimide type B using an eight step puddle/spray development process for 104 seconds. The nominal line size is six microns with ± 10% control limits.
Figure 13: Focus and exposure matrix of 6 micron lines and spaces in polyimide type A.
Figure 14: Focus and exposure matrix of 6 micron lines and spaces in polyimide type B.