Optimization of Photosensitive Polyimide Process for Cost Effective Packaging

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Recent developments in the use of photosensitive polyimide (PSPI) and in the associated exposure equipment have expanded the applications of photosensitive polyimide in the semiconductor industry. The thermal and dielectric characteristics of photosensitive polyimide are compatible with the requirements of semiconductor devices. Various kinds of technologies and materials have been developed and utilized for interlevel insulation, buffer, and α-ray shielding layers of semiconductor devices.

The stress buffer application has been accepted by the industry for many years and has achieved a very good reliability history since its introduction for plastic packages [1]. This application uses a thick film of polyimide as a buffer layer between the passivation layer of the device and the molding material of the plastic package. The thick film of polyimide absorbs the stress imposed by the molding resin for which thermal coefficients are larger than that of the silicon chips and lead-frames.

Traditionally, the polyimide lithographic process involves a trilayer film consisting of an adhesion layer, a polyimide film, and photoresist. The advanced development of photosensitive polyimide has opened a new door for semiconductor manufacturers to realize significant cost savings. Using photosensitive polyimide can substantially reduce the total number of process steps used in the traditional polyimide process. John Rose [2] has reported that photosensitive polyimide offers reduced process times and superior results compared with nonphotosensitive polyimide. For some applications, the use of photosensitive polyimide consolidates the passivation and polyimide lithography steps into one process level. This translates into process simplification and manufacturing cost reduction. Consequently, there has been a rapid increase in the use of photosensitive polyimide in the semiconductor industry.

Although the absolute critical dimension (CD) resolution for the polyimide level is relatively large, the thickness requirement and the negative tone characteristics of the film impose challenges to polyimide process development. For example, the resolution of small features such as fuse windows in DRAMs combined with thick photosensitive polyimide, results in a large height-to-linewidth aspect ratio that is comparable to many photoresist applications. Also, residual film formation, which is commonly found with negative tone resist, has to be minimized.
Warren Flack et al. [3] presented the characterization results of properties of two commercially available photosensitive polyimide films. This paper will present further characterization results for one of these materials at different thicknesses using basic photoresist characterization techniques.

Process optimization results and lithographic performance of a commercial polyimide product was studied at three different thicknesses, 10, 15, and 20 microns. Cross sectional SEM analysis and Bossung plots were used to establish lithographic capabilities. These experimental results were used to study the effects of polyimide film thickness on lithographic performance.

1.0 INTRODUCTION

1.1 Plastic Package Reliability and Yield Issues

Use of a plastic package offers lightweight, low cost packaging capability to semiconductor manufacturers. However, one of the major drawbacks of plastic package technology is the stress imposed by a molding resin for which thermal expansion coefficients differ from those of the silicon chips and lead-frame. These stresses in plastic packages without polyimides can lead to quality problems such as “passivation cracking, metal deformation and fatigue, parametric shifts such as offset voltages, resistance of thin film transistors, and pitch-off voltages, hot electron degradation and mechanical failure.” [4]

Another important failure mode due to plastic molding resin is often found in DRAM applications. Fillers in the resin can cause point stresses on the surface of the chip that result in single-column-line failure [5]. This phenomenon is known as “filler-induced stress” and is illustrated in Figure 1.

Both of these failures, which create reliability and yield problems, can be avoided by applying a thick film of polyimide as a buffer layer between the active devices and the plastic molding. A cutaway plastic package showing the exposed polyimide and the underlying device is shown in Figure 2. In addition, this thick polyimide layer can be used to eliminate the filler-induced stress by protecting the die from the coarse composition of the molding compound (see Figure 3).

1.2 Conventional Polyimide Application

Conventional, or nonphotosensitive polyimide cannot be directly patterned and requires several process steps after the active device is created. 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. A thick film of polyimide is spun on the wafer using a dispense technique similar to the photoresist process. Next, a thin layer of photoresist is applied and
exposed by a photolithography tool. A standard resist develop process is used to define the pattern. This pattern is again transferred to the polyimide layer by wet etching through the windows opened during the photoresist lithography step. The wet etch is an isotropic process that causes critical dimension and sidewall control problems. This technical difficulty combined with the complexity of the process have limited the nonphotosensitive polyimide application.

1.3 Simplified Photosensitive Polyimide Process

Use of photosensitive polyimides offer a cost savings alternative to the buffer coat polyimide application. Photosensitive polyimides can be processed similar to standard resists using photolithography techniques. A demonstration of this process simplification is as shown in Figure 4. An eight-step conventional polyimide process can be consolidated into a three-step process using photosensitive polyimide.

In addition to providing process simplification, this three-step process offers the significant advantages of superior resolution and improved sidewall profiles [2]. Use of photosensitive polyimide can also eliminate one photolithography level in the manufacturing cycle. Figure 5 shows a patterned polyimide layer used as an etch mask for the passivation layer. In this example, two lithography levels and a total of six process steps are eliminated by the photosensitive polyimide approach. As a consequence, cycle time and chemical consumption are reduced. All of these advantages translate into cost savings, ease of use, higher throughput, and better quality.

1.4 Types of Photosensitive Polyimide

Photosensitive polyimide, like photoresist, can be divided into two types, negative or positive acting. Application of positive photosensitive polyimide is limited because of the narrow film thickness range available. Negative photosensitive polyimides are available in a wide range of viscosities [6]. These negative photosensitive polyimides can be divided by their chemistry into two main categories. Details have been reported by W. Flack et al. [3].

1.5 Photolithography Requirements of Photosensitive Polyimide Process

In general, the photolithography requirements of a photosensitive polyimide stress buffer level are less demanding in both resolution and overlay budget than other lithographic levels. Resolving large bonding pads on the order of 100 μm square with overlay requirements as large as several microns is common. However, resolving small features such as 15 μm fuse windows in films greater than 30 μm thick for DRAM applications can be very challenging. This high aspect ratio of more than 2:1 is comparable to those found in more advanced photoresist applications.

Large depth of focus (DOF) is required to accommodate large topography differences on the wafer as well as the thickness requirements of the polyimide film. As the wafer approaches the final stage of the fabrication process, topography difference across the wafer can be significant. This can cause the polyimide thickness to vary widely across the wafer, which adversely affects
critical dimension (CD) control. Furthermore, the bulk absorption effects and the thickness of the polyimide can reduce the effective dosage at the bottom of the polyimide film.

In order to establish a robust buffer layer photosensitive polyimide process, process optimization must be carefully performed with the appropriate lithography tool and polyimide material. In this paper, the results of an optimized process on a commercially available photosensitive polyimide using a high throughput gh-line stepper will be presented.

2.0  EXPERIMENTAL METHOD

A commercially available g-line photosensitive polyimide based on the Siemens chemistry was examined. Focus/exposure process windows, and sidewall profiles for three different thicknesses, 10 μm, 15 μm, and 20 μm were studied.

An Ultratech Titan Wafer Stepper® was the exposure tool of choice for this application. This stepper is based on the patented 1X Wynne-Dyson lens design using broadband g- and h-mercury lines including the wavelength continuum from 390 to 450 nm [7]. This is a very efficient optical design which consists of five optical elements and delivers very high intensity light at the wafer plane. It 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 [8].

Six inch bare silicon wafers were used for the experiments. Wafer layout for the focus/exposure matrix is shown in Figure 6. This is an 11 x 11 matrix with field dimensions of 10 x 10 mm. Focus was varied from -8.75 to +6.25 μm with 1.5 μm increments. Exposure dosage was varied from 850 to 2350 mJ/cm² with 150 mJ/cm² increments for this PSPI material. The nominal dose was approximately 1600 mJ/cm².

Before the actual experiments, the exposure tool was tested for: (1) exposure dosage uniformity across the maximum exposure field, and (2) exposure dose repeatability. The results are shown in Figures 7 and 8 respectively. A spin curve for this PSPI material was generated and is shown in Figure 9. Spin speeds were then chosen to achieve the required thicknesses of 10 μm, 15 μm, and 20 μm.

Polyimide was applied using a Solitec 5110C system. No HMDS vapor prime was used on the wafer because it is not an effective adhesion promoter for polyimides. The dispense procedure included a static dispense, a ten second spread cycle at 700 rpm, and a thirty second final spin. Different final spin speeds were chosen to achieve the three desired final thicknesses of 10, 15, and 20 μm. The coated wafers were softbaked using a Solitec hotplate bake unit. Different temperatures were selected depending on the desired thickness of the film. After softbake, the film was measured using a Sloan Dektak 3030 profilometer. Development was done using a Solitec spray develop system. The developer and rinse used were as recommended by the material vendor. The process conditions are shown in Table 1.
Table 1: Process Conditions for Three PSPI Films with Different Thicknesses

<table>
<thead>
<tr>
<th>Thickness (µm)</th>
<th>Spin Speed (rpm)</th>
<th>Soft Bake (Temp/Time)</th>
<th>Overlap Time (sec)</th>
<th>Development Time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>4000</td>
<td>60°C/3’, 85°C/3’</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>15</td>
<td>2700</td>
<td>60°C/3’, 90°C/3’</td>
<td>10</td>
<td>17</td>
</tr>
<tr>
<td>20</td>
<td>2200</td>
<td>60°C/3’, 95°C/3’</td>
<td>10</td>
<td>25</td>
</tr>
</tbody>
</table>

The polyimide critical dimension (CD) was measured using an Amray Model 1830 Scanning Electron Microscope (SEM). Cross-sectional analysis was done using a Hitachi 570 (SEM). SEM micrographs were taken at nine fields in the focus/exposure matrix (refer to Figure 6).

3.0 RESULTS AND DISCUSSION

Bossung plots for six micron lines in three different thicknesses of PSPI are shown in Figure 10, 11, and 12 respectively. Lines showing the ±10 percent CD limits are shown on each figure. Isofocal point appeared to be about 10 - 15 percent into the film from the surface. All three charts show very good process latitude across the whole focus/exposure range. For 10 and 15 µm PSPI films, a 10 percent bias in the reticle design can be applied to achieve the nominal target of 6 µm equal line/space pairs at a nominal exposure dose of 1600 mJ/cm². For 20 µm thick films, a higher exposure dose, larger than 2200 mJ/cm², has to be applied to achieve the nominal CD target.

Focus/exposure plots for +/-10 percent CD control are shown in Figures 13, 14, and 15 respectively for the three thicknesses. Processes can be designed around these plots to give the best combination of focus and exposure latitude. The process window is shown by the large rectangular box that fits inside the contours. For example, one can design a process that allows for 30 percent exposure dose variation with more than 8 µm focus latitude in the 10 µm thick PSPI film.

SEMs of 6 µm line/space pairs under different process conditions are shown in Figures 16, 17, and 18. Figure 16 shows two 20 µm PSPI samples exposed at 1000 and 2200 mJ/cm². The bottom SEM clearly shows that the PSPI film was underexposed and that the thickness was less than the sample exposed by the higher dose. Process development for the thicker film can be optimized by studying a higher exposure dosage range. Figure 17 shows 6 µm line/space at three different thicknesses. Figure 18 includes SEMs showing results through the focus and exposure ranges studied. SEMs in the horizontal direction show patterns from -7.25 µm focus bias to +4.75 µm (from left to right). SEMs in the vertical direction show patterns from 2200 mJ/cm² to 1000 mJ/cm² (from top to bottom).
4.0 CONCLUSION

There is a rapid increase in the use of photosensitive polyimide in the semiconductor industry. Because its thermal and dielectric characteristics are compatible with the requirements of semiconductor devices, PSPI has been utilized for interlevel insulation, buffer, and α-ray shielding layers.

Of these different PSPI applications, the stress buffer application dominates. It offers the advantages of yield improvement by minimizing local stress, and cost savings by reducing the number of process steps. The improvement of sidewall angle of PSPI films offers yet further cost savings by consolidating the passivation and polyimide lithography steps into one process level.

This paper has shown the process conditions and results for three different thicknesses of a commercial PSPI material. Bossung plots illustrated that a large focus and exposure latitude was achievable for all three thicknesses of PSPI films, 10, 15, and 20 µm. For example, a process can be designed for 15 µm thick PSPI with 10 microns depth of focus and 20 percent exposure latitude for 6 micron lines with ± 10 percent CD control limits. Although increases in both focus and exposure latitudes are realized with thinner films, the process latitude and focus latitude losses associated with thickness increases have been shown to be minimal. Therefore, with mask bias corrections, 20 µm thick PSPI films can be easily patterned. Future efforts in the 20 µm plus regime are planned.

5.0 ACKNOWLEDGEMENTS

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6.0 REFERENCES


Figure 1: “Filler-induced stress”.

Figure 2: Cut-away plastic package showing the exposed polyimide, which is used as a stress buffer coating, and the underlying device.
Figure 3: Cross section of a CMOS device in a plastic package with photosensitive polyimide used as a stress buffer coating between passivation and molding compound.

Figure 4: Process simplification opportunity using photosensitive polyimide as compared with conventional nonphotosensitive polyimide.
Figure 5: Further process simplification using photosensitive polyimide as an etch mask for the passivation layer.
Figure 6: Wafer map showing the focus exposure matrix. The exposure dosage was varied from 850mJ/cm\(^2\) to 2350mJ/cm\(^2\) with 150mJ/cm\(^2\) increments. Focus was varied from -8.75 \(\mu\)m to 6.25 \(\mu\)m with 1.5 \(\mu\)m increment.

Figure 7: Wafer plane intensity uniformity (±1.06%) across 50 x 25 mm field.
**Figure 8**: Histogram of exposure dose. Range of variation within 0.34% of target dose.

**Figure 9**: Spin curve for PSPI studied.
Figure 10: Bossung plot for 10 μm PSPI film. The nominal line size is six microns with ±10% control limits.

Figure 11: Bossung plot for 15 μm PSPI film. The nominal line size is six microns with ±10% control limits.
Figure 12: Bossung plot for 20 μm PSPI film. The nominal line size is six microns with ±10% control limits.

Figure 13: Focus/Exposure process latitude for 10 μm PSPI film.
Figure 14: Focus/Exposure process latitude for 15 μm PSPI film.

Figure 15: Focus/Exposure process latitude for 20 μm PSPI film.
Figure 16: Six micron line/space pairs SEM cross-section pictures at 20 µm PSPI film (Top: 2200 mJ/cm², Bottom: 1000 mJ/cm²). Focus = -1.25 µm
Figure 17: Six micron line/space pairs SEM cross-section pictures at 10 µm, 15 µm and 20µm PSPI film.
Figure 18: Six micron line/space pairs SEM cross-section pictures at 10 μm PSPI film
(Left to right: -7.25 μm to +4.75 focus bias; Top: 2200 mJ/cm², Bottom: 1000 mJ/cm²; Center: -1.25 μm focus bias and 1600 mJ/cm²).