PLANARIZATION OF MICROELECTRONIC STRUCTURES BY USING POLYIMIDES

Ladislav Matay* — Róbert Andok**

In the recent years there has been an increasing demand for new types of polyimides which could planarize topographies of microelectronic structures by conserving all of their electro-physical properties for a given application. In this work, planarization properties have been examined for the PPID polyimide material. Profilometer technique has been used to measure step height changes of isolated lines of various dimensions. A model of local and global planarization has been completed. Thermogravimetric analysis (TGA) has been used to evaluate thermal processes in the PPID polyimide.

Key words: polyimides, planarization, degree of planarization, RIE, application

1 INTRODUCTION

In the recent years there has been an intensive and rapidly growing interest in spun-on polymer materials applicable as thin isolation or passivation films on semiconductor devices, replacing silicon nitride and silicon dioxide and other commonly used materials. Especially polyimides have gained their unique popularity in microelectronics and, comparing to inorganic dielectrics, one of the advantages of using polyimides as dielectrics is the ability of planarization of polyimide films over topographies by solution coating of polyimide [1]. Besides their low dielectric constant ($\varepsilon < 3.5$), so far best achieved degree of planarization (DOP) among all presently used materials, and improved adhesive power, still other superior properties of polyimides that have been reported in literature [1, 2] should be noted: insolubility, fine patterning, photo-sensitivity, high short-term resistance, good spin-coating, low water uptake, reduced stress and improved thermomechanical properties, and relatively low cost.

In general, there are two types of planarization that play an important role for lithography — local planarization, which is the ability to planarize closely spaced features; and global planarization, which is the ability to planarize topographies across a larger area or the whole wafer [2]. Ideal planarization that would yield a perfectly flat surface, regardless of the complexity and step variation of the underlying features, can never be achieved in practice.

Various authors [3–8] have dealt with the problem of planarization but quite often only local planarization or global planarization has been examined separately. The aim of this article is to give a summary of achieved goals for the local and global planarization simultaneously, while emphasis will be paid to the planarization properties of the used polyimide material (see more details in the text).

The degree of local planarization, as reported in [3], is determined by the ratio of the step height with the polyimide (PI) film to the initial height of the metal pattern; or by the slope of the resulting step.

Four different thicknesses are introduced (see Fig. 1): $h_m$ is the original step height and $h_s$ is the final polyimide step height, $T_{bot}$ is the polyimide thickness at the bottom of a step and $T_{top}$ is the maximum polyimide film thickness on top of the step. It is generally less than $T_{bot}$ provided that the line feature is small. The difference between the measured step height and the final step height ($h_m$ and $h_s$, respectively) gives the change in the polymer film thickness ($T_{bot} - T_{top}$). The ratio $h_s/h_m$ is often referred to as the Planarization Constant.

The degree of planarization (DOP), as defined in [4], is given by the following equation:

$$DOP = 1 - \frac{h_s}{h_m},$$

while

$$h_m - h_s = T_{bot} - T_{top}$$

where, as can be seen in Fig. 1, the differences between $h_m$ and $h_s$ are equal to those between $T_{bot}$ and $T_{top}$, respectively. Another factor that is often used in literature for defining the DOP is the angle $\theta$ of the resulting step, which can be calculated as:

$$\text{tg} \theta = \frac{2h}{w},$$

where $w$ is the width of a step.

Global planarization, on the other hand, can be defined as the long range effects over a wide patterned area [3].
of the fact that polyimides are applied as liquids, the surface is kept flat by the surface tension (Fig. 2a). Shrinkage due to the solvent loss or cure results in partial recovery of the underlying features (Fig. 2b) and thus the achievable DOP is controlled mainly by shrinkage [6]. From here on only variations over a positive topography with height \( h_m \) are considered. The thickness of the solution over a step after spin-coating of polyimide is then \( T_{bot} - h_m \).

After polyimide coating has been dried and cured, shrinkage of the coating occurs, leaving a film with thickness \( \delta(T_{bot} - h_m + h_s) + h_m \), which is a fraction of the original thickness \( T_{bot} \) [3]. Here, also the contribution of the final polyimide step height is considered. Table 1 is showing polyimide thickness variations over positive topography (i.e., features which are above the surface of a wafer).

To base our theoretical calculations on, we consider that the thickness of the polyimide \( T_{bot} \) over the wafer is much greater than the height of the features \( h_m \) over which material will flow during cure.

When small steps are close enough together, the thickness over the steps will not be the same as over the plain areas. As reported in [3], the resultant thickness will be the total volume of polyimide together with steps divided by the area of the region. If this area has a repeating unit (e.g., a chip), the polyimide thickness \( T_{chip} \) can be calculated for a representative unit (Fig. 3a,b) as follows:

\[
T_{chip} = \delta T_{bot} + [\delta h_s + (1 - \delta)h_m] \frac{A_{step}}{A_{chip}},
\]

where \( A_{step} \) is the area occupied by the steps in the chip area.

Based on these assumptions, the pattern density \( D \) can be calculated as \( A_{step} / A_{chip} \), while the corresponding two areas can be expressed from the given length, width and spacing of the steps.

Thus, referring to [3] with slight modifications, the model of simple global planarization can be defined. In general, there are two cases which should be considered for the pattern density \( D \):

(a) If we consider that area units (chips) are repeated in two dimensions (see Fig. 3b), the global pattern density for the whole wafer will be

\[
D = \frac{\sum A_{chip}}{A_{wafer}},
\]

where \( A_{chip} \) and \( A_{wafer} \) are the total area of all chips and the area of the whole wafer, respectively.

(b) On the other hand, if we consider only one-dimensional repeating of the steps (e.g., in horizontal axis \( x \)) within a unit (chip), the formula for the local pattern density for steps in that unit (see Fig. 3a) can be expressed as

\[
D = \frac{\sum A_{step}}{A_{chip}} = \frac{w}{w + x} = \frac{1}{1 + \frac{x}{w}},
\]
In order to use polyimides as isolation materials it is important to know their planarization properties. In our experiments a polyimide material of additional type has been used which was synthesized in our institute and named as PPID. This polyimide solution has been diluted in dimethylformamide (DMF) in accordance to the technological requirements and three different solutions of the PPID polyimide have been used (i.e., 30%, 35%, 40% and 55% solutions).

Table 2. Testing modules for planarization

<table>
<thead>
<tr>
<th>Testing module</th>
<th>w [μm]</th>
<th>l [μm]</th>
<th>x [μm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>I.</td>
<td>5</td>
<td>2000</td>
<td>180</td>
</tr>
<tr>
<td>II.</td>
<td>20</td>
<td>2000</td>
<td>170</td>
</tr>
<tr>
<td>III.</td>
<td>40</td>
<td>2000</td>
<td>150</td>
</tr>
<tr>
<td>IV.</td>
<td>100</td>
<td>4000</td>
<td>300</td>
</tr>
</tbody>
</table>

For this purpose four different testing modules have been fabricated. Each module consisted of a set of five Al lines with different widths and spacings between them. Table 2 is showing these modules for planarization; here w and l are the width and length of the lines, respectively, and x is the spacing between these lines.

The testing aluminium structures with thicknesses from 0.7 to 1.2 microns have been deposited by e-beam evaporation on cleaned silicon wafer, on which a 100 nm thick layer of SiO₂ has been thermally grown. To measure the profile variations of the evaporated aluminium lines the Talysstep measurement system by Rank-Taylor-Hobson with 2 nm resolution has been used. Then a solution of polyimide has been spin-coated using 3000 ± 5000 rpm for 30 seconds.

Experimentally, three types of thermal processes have been examined. All of the three processes had one thing in common, that is, that the wafers have been dried at 140 °C for 20 minutes in an electrical oven with the aim of partial removal of the diluent.

The temperature regime I was characterized by dividing of the whole wafer in eleven parts which were inserted into the electrical oven, where the temperature grew up continuously from 24 °C to 275 °C with the rate of 3 °C per minute. During the increasing temperature, these parts have been one after the other taken off from the oven and thickness of the polyimide film has been measured. This process is shown in Fig. 4.

In the temperature regime II the wafer has again been divided in eleven parts. Each part of the wafer with applied polyimide film has been put in the oven with temperature interval set from 30 °C to 275 °C and taken off after 12 minutes of curing. The thickness of polyimide film has been measured afterwards (Fig. 4).

As can be seen in Fig. 4, in the temperature regime I, where the thin polyimide film has a constant thickness, the temperature interval is between 25 °C and 185 °C. When this temperature has been exceeded the polyimide thickness decreases until it reaches 20 % less thickness (at 272 °C) comparing to its initial value.

Comparing to the previous case, in the temperature regime II, the thin polyimide film has a constant thickness within the interval of 25 °C to 145 °C.

After reaching the temperature of 145 °C, the polyimide thickness decreases until it reaches 19.42% less thickness (at 232 °C) comparing to the initial thickness of the polyimide (before it was put in the electrical oven). The relative decrease of the polyimide film between the
two temperature regimes is caused by different times of curing of polyimide films at the same temperature.

In the next experiment the influence of long-term constant temperature dependence on the relative thickness change of polyimide films has been examined (temperature regime III). Three silicon wafers have been coated with three different concentrations (30%, 40% and 55%) of the PPID polyimide solution. All wafers have been thermally cured at 150°C for 30 minutes. The samples prepared in this manner have been divided into eight parts and annealed at 220°C in nitrogen atmosphere. All parts of the wafers have been gradually removed from the oven and polyimide thickness has been measured. The corresponding data are plotted in Fig. 5.

Figure 6 shows experimental results of the relative decrease of polyimide thickness in dependence on the concentration of the polyimide solution. It can be seen in Figs. 5 and 6 that the relative change of the polyimide film thickness increases in accordance with the decrease of the polyimide solution concentration.

3 RESULTS AND DISCUSSION

3.1. Results on local planarization

The dependence of DOP on the width of the planarized lines for local planarization is illustrated in Fig. 7. As can be seen in this figure, the dependence has a logarithmic character. The dependence has been obtained from the measured data and the resultant characteristic has been fitted by Eq. 7 where \( \alpha \) and \( \beta \) are fitting constants and \( w \) is the corresponding width of the planarized aluminium lines.

As can be seen in Fig. 7, the curves labelled as A, B, C and D, E, respectively, show similar dependence. In general, for the same width of the planarization line, the

![Fig. 5](image1.png) Relative decrease of polyimide thickness versus time of the thermal cure at constant temperature of the annealing for three different concentrations of the PPID solution.

![Fig. 6](image2.png) Relative decrease of the polyimide thickness versus corresponding concentration of the polyimide solution.

![Fig. 7](image3.png) Degree of planarization in dependence on the width of the planarized lines.

![Fig. 8](image4.png) Planarization constant versus pattern density.
samples D and E were of a better degree of planarization comparing to samples A, B and C. This difference in the $DOP$ was caused by the different thickness of the planarizing polyimide film (samples D and E had 1.56 $\mu$m and samples A, B and C had 1.36 $\mu$m of PI thickness, the homogeneity of thickness used polyimide is below 1%).

$$DOP = -\alpha \ln w + \beta,$$  \hspace{1cm} (7)

Theoretically, it can be said that the thicker the polyimide film is, the better the degree of planarization can be achieved.

### 3.2 Results on global planarization

Figure 8 shows the dependence of the planarization constant on the pattern density, calculated by Eq. 6. It is evident that by increasing pattern density $D$ also the planarization constant will increase.

### 4 CONCLUSION

The planarization properties have been examined for the new PPID polyimide material. Thin polyimide films were prepared by spin coating on to the surface of Si wafer with testing aluminum structures. The thermogravimetric analysis (TGA) has been used to evaluate the thermal processes in the PPID polyimide. Profilometer technique has been used to measure step height changes of isolated lines with various dimensions. Theoretically, it can be said that a thicker polyimide film will lead to better degree of planarization. Also a model for local and global planarization has been revised.

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### REFERENCES


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