Roughness reduction in submicron waveguides by low-molecular weight development

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Abstract

Roughness reduction of a submicron waveguide profile in chemically amplified negative resist is here performed by proper selection of an alkali-based developer, taking into account that its smaller molecules lead to smoother resist surface by altering the developing mechanism of aggregate extraction performed with standard quaternary ammonium hydroxide. Roughness is then analyzed by means of classical Atomic Force Microscope inspection; furthermore, a non-invasive line edge roughness analysis approach based on top-down scanning electron microscope acquisition gives comparable results, in terms of standard deviation and molecular aggregate periodicity.

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1. Introduction

The ever decreasing feature size on wafers is strongly pointing out roughness as one of the most critical issues for controlling propagation loss in optical devices: in fact Line Edge Roughness (LER) has shown up itself as a standard topic for its possible yield impact on wafer production. Apart from material intrinsic roughness, many factors within the technological process push its increment, above all during lithographic process: in literature lithographic strategies for roughness reduction (multiple exposure technique, hardbake and UV postprocessing [1], conditioned rinse [2]) are well known, but above all the interaction between resist and developer chemicals can be held as main responsible for feature profile roughness. In particular it has been shown that developers with low molecular weight can more easily break the molecular aggregates in resist, leading to much smoother surfaces.

In this work roughness reduction in a submicron resist waveguide is successfully performed by means of a potassium hydroxide developer; the profile roughness standard deviation and resist aggregate periodicity will be analyzed both by direct Atomic Force Microscope (AFM) inspection and by LER analysis on top-down Scanning Electron Microscope (SEM) acquisitions.

2. Polymer aggregates in resist films

Surface roughness in resist films can be well described through a granular structure, where granules...
are polymer aggregates whose size and shape depend both on the resist itself and on its interaction with developer [3]. Such roughness carries out a linewidth fluctuation, that is to say surface roughness and profile variation have the same origin. Their contribution becomes important on a nanometric scale: in fact the typical size of molecular aggregates is around 20–30 nm.

Linewidth fluctuation is due to the aggregate extraction process during development, and its standard deviation can be reduced by using development solution with proper molecular size [4]. In our case, the resist is chemically amplified negative Sumitomo HN-432, spun on a silicon substrate at 4000 rpm with a resulting 135 nm thickness: a 600 nm-waveguide is exposed by means of a 266 nm-direct writing laser with a typical clearing dose of 50 mJ/cm², the post exposure bake step being performed at 96° for 60 s. The development step is conducted both with typical metal ion free tetramethylammonium hydroxide (TMAH)-based development and a potassium hydroxide (KOH) solution: these two developers have been chosen, as they are the most diffused ones in semiconductor manufacturing process. They hold both for standard and chemically amplified resist: in fact almost all commercially available formulas contain either quaternary ammonium hydroxide or alkali metal based solutions, as they are the first choice when formulating water-based wafer processing wet chemicals that must contain a base to raise the pH above neutral. The two developers are both strong organic bases (pH > 13), but with different molecular weight: TMAH molecule is quasi-centrosymmetric and has a molecular weight of 91 g/mol (Fig. 1a), while single-bonded KOH (Fig. 1b) is a low-weight molecule (56.11 g/mol) that can easily break bonds in resist aggregates, thus reducing overall roughness. The development is performed either in TMAH 2.38% for 35 s or in a 1:2 AZ400K (around 15% KOH)/DI water solution for 10 s. As already known in literature, the development time and concentration have an impact on resist roughness [5], as well as the exposure dose: in particular AFM analysis shows that surface roughness increases with developer concentration, while it is only slightly affected by varying development time. So a solution with low TMAH content, as in our case, is the best available in order to get reduced roughness, while the use of a highly concentrated developer as AZ400K (usually suggested to be diluted in four parts of DI water) represents a worst case to be compared to. In this work even such KOH high concentration condition will demonstrate to offer a surface smoothing behaviour with respect to quaternary ammonium hydroxide development.

3. Roughness analysis

The first roughness analysis approach is the classical one with direct surface topography inspection using AFM: in such case the waveguide has been exposed at

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**Fig. 1.** Molecular composition of tetramethylammonium hydroxide (a) and potassium hydroxide (b).
half the optimal dose (25 mJ/cm²) in order to scan the
top of the structure instead than sidewalls, which would
require a not so easy and destructive cleaving step [4].

The AFM acquisitions related to TMAH develop-
ment (Fig. 2) and KOH one (Fig. 3) validate the stronger
roughness in the TMAH case, due to the presence of
bigger aggregates.

The statistical parameters of roughness distribution
are reported in Table 1: the surface characteristics after
processing with both developers are compared with the
ones of unexposed sample. The standard deviation ($R_q$)
of the distribution is worse after development than in the
pre-exposure case (virtually smooth surface, roughness
comparable with instrument limits of 1 Å), but TMAH
sample roughness is around 3 nm, a factor of three
greater than KOH one.

The Power Spectral Density (PSD) function evaluated
on a single line of Fig. 2a (Fig. 4) shows a marked peak at
25 $\mu$m$^{-1}$ (period around 40 nm): so in TMAH case there
is a periodicity of resist molecular aggregates.

LER analysis of top-down SEM acquisitions [6,7]
can be usefully exploited to detect and quantify the
molecular aggregate distribution in the resist: through
pre-processing, quantization and thresholding of a
number of acquired images, the distance vectors
between real and fitted profile are calculated. In

Fig. 2a and b the extracted real profiles for,
respectively, TMAH-developed and KOH-developed
waveguide are superimposed on microscope acquisi-
tions, with the indication of calculated standard
deviation values for both right and left profiles: the
TMAH related values are roughly three times greater
than the KOH ones. The statistical analysis is

<table>
<thead>
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<th>Minimum (nm)</th>
<th>Maximum (nm)</th>
<th>Mean (nm)</th>
<th>$R_{pv}$ (nm)</th>
<th>$R_q$ (nm)</th>
<th>$R_a$ (nm)</th>
<th>$R_{sk}$ (nm)</th>
<th>$R_{ku}$ (nm)</th>
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<tbody>
<tr>
<td>Pre exp</td>
<td>1.456</td>
<td>2.33</td>
<td>1.848</td>
<td>0.87</td>
<td>0.17</td>
<td>0.13</td>
<td>−0.01</td>
</tr>
<tr>
<td>TMAH dev</td>
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<td>17.42</td>
<td>10.50</td>
<td>13.54</td>
<td>3.36</td>
<td>2.85</td>
<td>−0.01</td>
</tr>
<tr>
<td>KOH dev</td>
<td>2.02</td>
<td>7.09</td>
<td>4.63</td>
<td>5.07</td>
<td>1.18</td>
<td>0.97</td>
<td>0.00</td>
</tr>
</tbody>
</table>
performed on a distance vector averaged over different portions of the waveguide itself, and represents the roughness systematic contribution. In particular the evaluation of its power spectral density reveals the existence of periodicities in the real profile, as PSD function is the discrete Fourier transform of autocorrelation vector. The PSD function shows its characteristic form, with a substantially flat behavior until the inverse of correlation length and rapidly decreasing at higher spatial frequencies: the slope of the linear envelope is related to the relative weight of high spatial frequency components with respect to low ones in the waveguide profile itself. In Fig. 6, solid green curve is related to TMAH case, showing a marked periodicity with a first harmonic spatial frequency $f_1$ at $10^{-1.59}$ nm$^{-1}$ (around 40 nm), while the dashed blue and the solid red curves are related to KOH development, where only a small overelongation is present. The TMAH curve itself clearly shows also second ($f_2 = 10^{-1.32}$ nm$^{-1}$) and third harmonic ($f_3 = 10^{-1.08}$ nm$^{-1}$) related peaks. It is evident that both standard deviation and periodicity values correspond to the ones determined via AFM inspection, but they can be obtained with a simple and non-invasive technique.

4. Conclusions

In this paper roughness reduction on a submicron real waveguide profile in chemically amplified negative resist HN-432 has been performed: the use of resist developers with different molecule size, tetramethylammonium hydroxide and potassium hydroxide, confirmed that lighter and smaller molecules of the latter developer can lead to a reduction of profile standard deviation by a factor of three. Besides, LER on a top-down scanning electron microscope acquisition showed to be as precise as classical AFM surface investigation to determine standard deviation and profile periodicity, demonstrating to be a powerful, not invasive technique.

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References