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Research paper

A new approach to determine development model parameters by employing the isotropy of the development process

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ABSTRACT

There is an increasing demand for high-resolution three-dimensional (3D) structures as for instance micro-optical lenses or blazed gratings. The fabrication of these requires electron beam lithography for patterning. 3D structure shapes can be predicted by using simulation tools to reduce cost and development effort. For this, different resist models have been presented. However, currently available methods to determine the corresponding parameters are either time-consuming and, thus, costly or lead to ambiguous parameter values. This can lead to inaccurate simulation results in particular for 3D structures realised by greyscale lithography. In this paper, we introduce a novel and straightforward approach to determine improved resist model parameters. For this purpose, lateral resist erosion due to the isotropy of the development process is employed. By the example of the development model according to C. Mack for negative tone resists it is shown that our newly introduced test pattern is suitable to adjust model parameters.

1. Introduction

High-resolution, three-dimensional (3D) structures needed for the fabrication of e.g. micro-optical elements or microfluidic systems are becoming increasingly important for a vast range of research and industrial applications like optical systems, micro-optics or bioscience. A flexible and efficient approach to realise these 3D structures using only one lithographic step is greyscale electron beam lithography (EBL) [1].

In greyscale lithography, a dose-modulated exposure is used to cause a certain locally induced development rate for the resist. In this way, the remaining resist thickness and, thus, the 3D structure shape is controlled. The corresponding relationship between dose and development rate is usually determined experimentally by either a development rate monitor using laser interferometry during the development step [2] or by measuring the contrast curve on the fully processed substrate [3]. For an efficient realisation of high-resolution 3D structures it is useful to employ simulation tools to predict resulting profiles in advance. These tools rely on the exact knowledge of dose dependent resist development rates for which various models have already been introduced [4,5]. One of those models is the Mack model [6], which proved to describe our experimental results very well. The respective model parameters are usually determined by fitting the experimentally obtained contrast curve. However, this method leads to a large ambiguity of Mack parameters and hence to inaccurate simulation results at least for certain high-resolution 3D structures. In this paper, we introduce a novel approach to determine more accurate resist parameters for the Mack model with the help of an easily applicable test pattern. We employ the isotropy of the development process and analyse the lateral and vertical resist erosion, which reveals important information about high development rates that are not easily accessible from the mere contrast curve. These data reduce the degrees of freedom of the Mack parameters, which leads to a more stable fit and improves the agreement of measurement and simulation results.

2. Mack model and isotropy of resist development

The Mack model is a well-known mathematical representation for the relationship between development rate and exposure dose based on a simple kinetic modelling approach. The model we use for our simulations is the Mack model for negative tone resists [7], which we name in the following Mack model for brevity. According to this model, the resist development is an isotropic process with the rate

$$\begin{aligned} r_{dev} &= R_{\max}\left(1-\frac{(a+1)(1-m)^n)}{a+(1-m)^n}\right)+R_{\min}, \quad \text{with} \\ a &= \frac{n+1}{n-1}(1-m_{\text{th}})^n \quad \text{and} \\ m &= \exp(-dose \cdot Dill_C), \end{aligned} \tag{1}$$

where

- m is the relative photoactive compound (PAC) concentration, which is related to the exposure dose and the exposure rate constant and third

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Dill parameter $Dill_C$,

- R_{max} the maximum development rate for unexposed resist,
- R_{min} the minimum development rate for fully exposed resist,
- n the dissolution selectivity parameter, which states the amount of exposure events necessary to inhibit the dissolution of one resin molecule of the resist, and
- m_{th} denotes the threshold photoactive compound concentration.

A common method to determine these so-called Mack parameters is to measure the contrast curve, i.e. the remaining resist thickness on the substrate after the development step as a function of the exposure dose. Different development times can be utilised to obtain more data points. To be able to neglect the proximity effect and disturbing effects at the edges, sufficiently large, homogeneously exposed fields are used.

The respective Mack parameters can then be obtained from numerical fits to the measurement data. An example for a contrast curve is illustrated in Fig. 1(a). For negative tone resists, the resist will be completely removed within the development time if the exposure dose remains below a certain threshold value. This development time dependent threshold dose is called dose-to-dark (D_d). Consequently, from the contrast curve there is no information available about development rates which are induced by doses smaller than D_d illustrated by the highlighted area of Fig. 1(a). This inaccessible information allows multiple possibilities to fit the Mack model to the contrast curve and, thus, leads to an ambiguity of Mack parameters as it is illustrated in Fig. 1(b) and Table 1. However, for certain 3D patterns, it is useful to apply selected areas with development rates larger than r_{dev} (D_d) in order to achieve the desired profile. This is for example beneficial to control the slope of edge regions. That is why the highlighted dose range is also crucial for a correct simulation.

The Mack model itself does not contain any anisotropy. Most data preparation algorithms, not only for greyscale lithography, assume a perfect anisotropy of the development process, though. That is, the assignment of exposure doses is purely based on the contrast curve also taking into account the proximity effects. However, since there is also lateral resist erosion, a decreased dose leads to both the intended decreased height and a reduced width of the structure. This fact is especially significant if the width of a structure is in the same order of magnitude as its height or even smaller.

Therefore, the lateral resist erosion is crucial for the final structure profiles. For this reason, we take it as a measurable quantity and use it to determine the so far inaccessible development rates for low doses and, thus, derive better resist parameters for the Mack model.

Table 1
Three different sets of Mack parameters obtained by numerical fits of an exemplary contrast curve depicted in Fig. 1(a). All three sets fit the contrast curve with about the same accuracy although there are large variations of parameter values.

	Set 1	Set 2	Set 3
R_{max} (µm s^{-1})	0.05	0.15	0.35
R_{min} (µm s^{-1})	$4\cdot10^{-4}$	$3\cdot10^{-4}$	$3\cdot10^{-4}$
m_{th}	0.43	0.64	0.80
n	5.44	3.14	2.28
$Dill_C$ (cm^2 a.u.$^{-1}$)	2.71	3.28	3.56

3. Lateral development effect and test pattern

To understand how the lateral development can be employed to extract more information about the resist we consider the patterning process of a line using a negative tone resist as depicted in Fig. 2. The line is exposed with a certain line dose LD which is larger than the background dose BD that is applied to both sides in the surrounding area. This leads to a small vertical development rate r_{v1} within the line compared to the vertical development rate r_{v2} outside the line. Due to the isotropy of the development process, the developer will attack the line from the side as well. Depending on the rate r_{v2} it will take some time till it can make its path to the edge of the line on substrate level and start to attack from there. As a result, a trapezoidal profile with a height h emerges after the development process. The bottom width w_b of the line strongly depends on the development rate r_{v2} and is hence a measure for the applied background dose. If we now choose the background dose such that it is smaller than the dose-to-dark D_d we will gain information about development rates which are not readily accessible from the mere contrast curve.

Our test pattern, thus, consisted of an array of lines with different widths varying from 0.5 µm to 6 µm. Both the exposure doses for the lines and the background were varied. The initial thickness of the used negative tone resist from an undisclosed manufacturer was approximately 2 µm on top of a silicon substrate. The exposure was carried out using EBL with a variable shaped beam writer Vistec SB4050 operating at 50 kV and a post exposure bake and puddle development step followed. The bottom width w_b of the resulting lines was measured by an in-line CD SEM Advantest LWM9000 and the height h with a Veeco Dimension 3100 AFM.

Since the investigated line widths are small compared to the range of the proximity effect it cannot be neglected. While this should only lead to a certain proportionality factor for the dose for each line width, the factor itself cannot be derived without further knowledge. However,

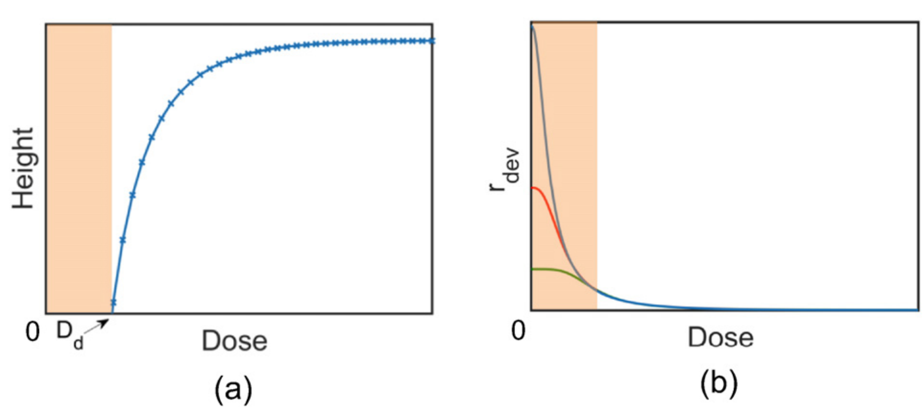

Fig. 1. Contrast curve and Mack model for negative tone resists. (a) The contrast curve shows the remaining resist thickness on the substrate after the development as a function of the exposure dose. It does not give information about development rates induced by doses smaller than D_d (highlighted area). (b) The Mack model describing the development rate as a function of the exposure dose is plotted for three different sets of Mack parameters (for corresponding values see Table 1). The curves significantly diverge in the highlighted area, whereas they still lead to the same contrast curve above D_d.