# Robust model-based approach for electron beam lithography process control

**Asya Asenova-Robinzonova, Elena G. Koleva**

*The present study is directed toward the investigates the dependency of the geometric characteristics of the developed post-exposure negative electron resist AR-N 7520 profiles on the parameters of the electron beam lithography process. Robust model-based approach is applied, considering the influence of process parameter variations under production conditions. This approach can be implemented for the improvement of the reproducibility of the resist profile quality characteristics and thus to enhance the quality of the constructed nanostructures.*

***Keywords – robust modelling, electron beam lithography, mean and variance models, negative electron resist AR-N 7520.***

***Моделно-базиран робастен подход за управление на процеса електроннолъчева литография (Ася Асенова-Робинзонова, Елена Г. Колева).*** *Настоящото проучване е насочено към изследване на зависимостта на геометричните характеристики на разработените пост-експонирани отрицателни електроноустойчиви профили AR-N 7520 от параметрите на процеса на електронно-лъчева литография. Приложен е моделно-базиран робастен подход, при отчитане на влиянието на вариациите на параметрите на процеса при производствени условия. Този подход може да бъде приложен за подобряване на възпроизводимостта на качествените характеристики на профилите на резиста и по този начин за подобряване на качеството на изградените наноструктури.*

## Introduction

Under production conditions, deviations in the output quality characteristics of the product can be attributed to various factors:

a) Production-related factors - human errors, variations in raw material characteristics, machine settings, changes in production parameters over time, measurement errors, etc.

b) Environmental factors - both during production and during product use.

c) Deterioration of output characteristics over time.

Additionally, under production conditions, the deviations in the process parameter settings and the presence of noise factors (uncontrolled factors) are more significant compared to laboratory conditions, and they impact the output characteristics of the product (quality indicators), leading to increased variability and decreased quality.

Quality improvement, defined as reducing the variability of the output characteristics due to errors in factor levels or changes in the uncontrolled factors, can be achieved by selecting appropriate optimal process parameters. This approach aims to ensure robustness (or insensitivity) toward errors in factor levels and other noise sources during the production process, ultimately enhancing product quality.

The evaluation of a mathematical model, describing the relationship between the quality characteristics and the process parameters can be based on known analytical relationships between the input factors and the output variables. However, it can also be empirically determined through experiments. Regression analysis [1], [2] is associated with the estimation of a quantitative relationship between input and output variables, as well as the performance of a statistical analysis of the resulting model to determine its adequacy in predicting the output variable.

Under production conditions, robust engineering approach is implemented and models for the mean values and variances of the output variables are estimated [2]-[4]. These models can then be used for parametric optimization, enabling the identification of process parameter settings ensuring robustness against sources of variability in the output variable. This approach can ameliorate the quality of the process or product without the need for improvement by expensive raw materials or equipment.

Electron beam lithography is the process of transferring a pattern onto the surface of a substrate by scanning a thin film (resist) on the surface by a tightly focused and precisely controlled electron beam (exposure) and then selectively removing the exposed or nonexposed regions of the resist in a solvent (developing). The process allows patterning of very small features, often with the dimensions of submicrometer down to a few nanometers. It can be implemented also for low and medium volume mask manufacturing [5], [6], which can be used in other lithography processes (e.g. photolithography).

The current report considers the electron beam lithography process for production of structures from the negative AR-N 7520 e-beam resist under production conditions. The AR-N 7520 e-beam resist is characterized by very high contrast, high resolution, excellent transfer of structures and high-precision edges. Investigation of the influence of input parameters, such as the electron beam exposure dose and resist thickness, on the linewidths of the developed after exposure negative electron resist profiles, is performed. This includes considering the impact of errors in the factor levels of process parameters and the sensitivity of the dimensions of the developed resist profiles toward such errors.

Based on the analyzed data from the experiment on the profile of the negative resist AR-N 7520 [7], a regression model is assessed for the resist profile linewidths [8], [9], considering the influence of the exposure dose and resist thickness as predictors. The regression model is then utilized to estimate models for the mean values and variances of the resist profile linewidths in production conditions. The estimated are implemented for the simulation of the developed profiles and the corresponding standard deviations at different exposure doses.

## Robust engineering approach

The robust approach for quality improvement under production conditions is based on experimental design methods. An experiment is conducted, based on a pre-defined plan, and a regression model for the quality indicator is estimated in relation to the process parameters. Afterwards, models for the mean values and variances of the output variable can be evaluated, allowing the consideration of the influence of the errors in the factor levels on the variation of the quality indicator.

The model of the mean value of the performance characteristic is [2], [3]:

$$(1) \qquad \tilde{y}(p) = E[y(z)] = \eta_m(p) + \theta^T E(g),$$

where $\eta_m(p)$ is a model of the performance characteristic, for example a regression model estimated using the results from a laboratory experiment. The second term takes into account the bias caused by the errors transmitted from the process parameters $p$ to the performance characteristic $\tilde{y}(p)$, where $\theta^T$ is the vector of the coefficients in the regression model ($\eta_m(p) = \theta^T F$), $F$ is a matrix of known functions $f$ (regressors' matrix) of the process parameters $p$, defined by the regression model and the performed experiments, $g = h - f$, $h$ is a vector of known functions of the regressors of the process parameters $z$, which are considered as containing errors $e$ (for any process parameter - $z_i = p_i + e_i$) and $E(g)$ is the mathematical expectation of $g$.

The model for the variance is:

$$(2) \qquad \tilde{s}^2 = E(\theta^T \psi \psi^T \theta) + \sigma_\varepsilon^2 = \theta^T \Psi \theta + \sigma_\varepsilon^2,$$

where $\psi = g - E(g)$, is defined on the basis of the variances for each process parameters $p$, which can be calculated using the tolerance limits of the process parameters, $\Psi = E(\psi\psi^T)$ depends on the structure of the regression model and the experimental design, $\sigma_\varepsilon^2$ is the random error of the performance characteristic.

The calculation of the error covariance matrix $\Psi = E(\psi\psi^T)$ is based on some assumptions about the mathematical expectation of the errors $e$: $E(e_i) = 0, E(e_i^2) = \sigma_i^2$, which can be defined by the tolerance limits.

## Experimental conditions

The process of electron beam lithography of negative electron resists is schematically represented in Fig. 1.

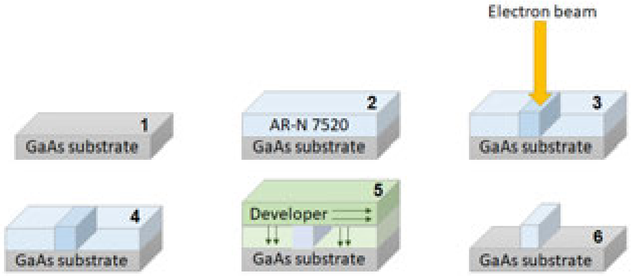

*Fig.1. Schematic representation of electron beam lithography process of negative electron resist AR-N 7520 profiles.*

The electron-sensitive resist (2), located on the substrate (1), is exposed to a specific dose of the electron beam (3). Then, the resist is developed (5) using a specific solvent (depending on the chemical composition of the resist). Depending on whether it is a negative or positive resist the irradiated volume of the resist remains or is dissolved. In Fig. 1 a developed negative resist with dissolved non-irradiated resist sections is presented.

The analyzed experiment was conducted on a ZBA23 (Raith) electron beam lithography system located in Bratislava, Slovakia. The negative electron beam resist used was AR-N 7520 (Allresist), and the electron beam had a variable cross-section and an energy of 40 keV [8], [9]. A thin film of the AR-N 7520 resist (Fig. 1) with a thickness of 460 nm was deposited on a GaAs substrate and exposed to the electron beam following a predefined pattern. The development process was performed using the AR 300-47 developer for 60 seconds. Several individual parallel lines with a width of 200 nm and a spacing of 600 nm were exposed with different exposure doses. During the development of the negative electron beam resists, the exposed areas become less soluble, while the unexposed areas dissolve after treatment with the developer. The geometric dimensions of the resulting nanostructure, specifically the width of the resist at different heights from the substrate (resist thicknesses), are being investigated.

The regression model for the linewidth of the resist after development, considering the factors in coded values (exposure dose - $p_1$ and resist thickness - $p_2$), was evaluated using the statistical software QstatLab [10]:

(3) $$\hat{y} = 255.06925 + 146.86958p_1 - 58.885466p_2 - 121.83284p_2^3 - 78.470074p_1p_2 - 59.079568p_1^2p_2 + 147.94979p_1p_2^2.$$

The estimated regression model is adequate and accurately describes the relationship between the output variable and the process parameters. It can be effectively used for prediction purposes. The range of variation for the two factors is as follows: the exposure dose ranges from $\tilde{p}_{1,min} = 120$ to $\tilde{p}_{1,max} = 250$ μC/cm$^2$, and the resist thickness ranges from $\tilde{p}_{2,min} = 0$ to $\tilde{p}_{2,max} = 474$ nm. The regression model (3) is estimated for process parameters in coded in the region [-1 ÷ 1] units. The relation between coded ($p_i$) and natural ($\tilde{p}_i$) values of the factors can be expressed by the equation:

(4) $$p_i = (2\tilde{p}_i - \tilde{p}_{i,max} - \tilde{p}_{i,min})/(\tilde{p}_{i,max} - \tilde{p}_{i,min}).$$

## Models for the mean and variance

Based on the estimated regression model (3), models for the mean value and variance of the resist linewidth under production conditions and the presence of errors in the factor levels have been evaluated – eq. (1) and (2). The variances of the process parameters are estimated, using their tolerance intervals. The tolerance limits of the factors in production conditions are shown in Table 1.

In Fig. 2 a contour plot of the mean value of the linewidth $\tilde{y}(p)$ as a function of the factors: exposure dose and resist thickness, is presented. Every vertical line drawn in this plot will correspond to a resist profile structure, obtained at exposure with the electron beam with a certain exposure dose.

**Table 1**

*Process parameters tolerance limits*

| Process parameter | Designation, coded | Tolerance limits |
|---|---|---|
| Exposure dose [μC/cm$^2$] | $p_1$ | $\tilde{p}_1 \pm 5\%\tilde{p}_1$ |
| Resist thickness [nm] | $p_2$ | $\tilde{p}_2 \pm 10$ |

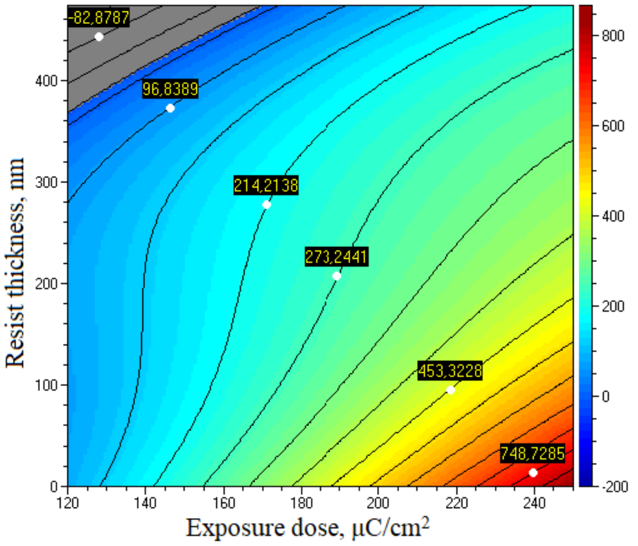

*Fig.2. Contour plot of the mean value of the resist linewidth $\tilde{y}(p)$ as a function of the exposure dose ($z_1$) and the resist thickness ($z_2$).*

From the graph, it can be observed that the maximum mean values are obtained at exposure doses above 220 μC/cm² and resist thickness below 40 nm. The minimum mean values are observed at low exposure doses ($z_1$ < 160 μC/cm²), regardless of the resist thickness. This indicates that the resulting structures from the developed resist have walls that are close to being parallel, which is one of the technological requirements for such nanoscale structures. At lower doses, there is also a loss of resist thickness after the development due to insufficient exposure to the electron beam (the gray zone).

Fig. 3 shows a contour plot of the variance of the resist width as a function of the two input process parameters. It can be observed that the minimum variance values are obtained throughout the entire range of exposure doses and resist thickness up to 150 nm. When working with exposure doses smaller than 160 μC/cm² (suitable for obtaining parallel walls), the variance in the upper part of the resulting resist structures is the highest.

From the contour plots, it is evident that the exposure dose and resist thickness are parameters that strongly influence the process and the geometric characteristics of the resulting profiles. It can also be observed that working with higher exposure doses - above 220 μC/cm², can improve the quality of the obtained profiles through electron beam lithography due to minimal variance values at production conditions. However, there will be a compromise in terms of the range of resist width variation for different resist thicknesses.

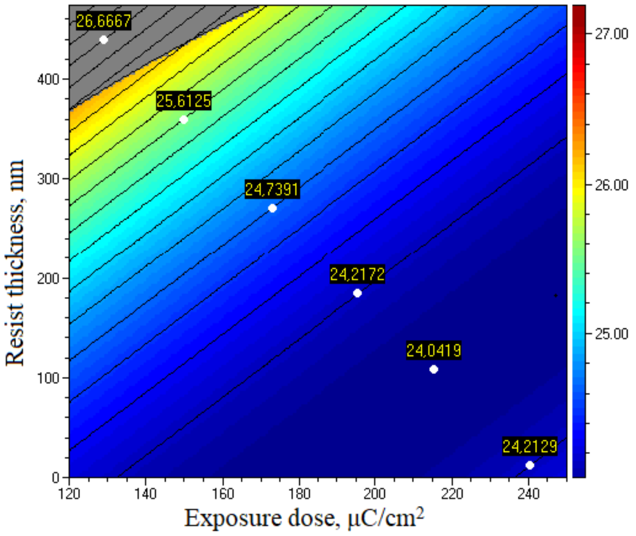

*Fig.3. Contour plot of the resist linewidth variance* $\tilde{s}^2$ *as a function of the exposure dose* $(z_1)$ *and the resist thickness* $(z_2)$.

## Conclusion

The applied robust approach for quality improvement under production conditions is based on reducing the variability of the output characteristics due to errors in factor levels or changes in the uncontrolled factors by selecting appropriate optimal process parameters. This approach aims to ensure robustness (or insensitivity) toward errors in factor levels and other noise sources during the production process.

Based on the estimated regression model for the AR-N 7520 resist profile linewidth from experimental data, models for the means and the variances of the resist profile linewidths under production conditions and the presence of errors in the factor levels have been evaluated. The obtained results show that working at higher exposure doses will lead to greater repeatability of the strictures under production conditions. On the other hand, the requirement for parallel sidewalls of the resist profiles determines the EBL process to be conducted at smaller electron doses.

If appropriate optimality criteria are defined, the estimated models for the mean and variance of the quality indicator will allow finding values of the parameters - exposure dose and resist thickness - that make the negative electron resist AR-N 7520 robust toward errors in factor levels and at the same time fulfil additional technological requirements for the produced structures.

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