Optimization of electron beam lithography processing of resist AR-N 7520

Elena Koleva[1,2*], Ivan Kostic[3], Lilyana Koleva[1], Katia Vutova[2], Irina Markova[1], Anna Bencurova[3], Anna Konecnikova[3], Robert Andok[3]

University of Chemical Technology and Metallurgy, Bulgaria[1]
Institute of Electronics, Bulgarian Academy of Sciences, Bulgaria[2]
Institute of Informatics, Slovak Academy of Sciences, Slovak Republic[3]

*eligeorg@uctm.edu

Abstract: *This work presents experimental and theoretical investigation of exposed and developed negative electron resist AR-N 7520 profiles using electron beam lithography system ZBA23 (Raith) at variation of the exposure doses and pre-defined exposure pattern. Several overall geometry quality criteria for the shape of the developed resist profile cross-sections are defined. Empirical models are estimated for the dependence of overall geometry characteristics of the obtained resist profiles on the exposure dose. These overall quality characteristics are used for defining of technological requirements for the formed profiles and for obtaining optimal regimes by multicriterial optimization.*
Keywords*: ELECTRON BEAM LITHOGRAPHY, EMPIRICAL MODELLING,MULTICRITERIAL OPTIMIZATION.*

1. Introduction

Electron beam lithography (EBL) is a key technology for the fabrication of advanced integral circuits and devices of electronics, photonics and nanoengineering. The experimental investigations and the computer simulation of the processes of electron exposure and development of the resist profile in EBL are very important for the optimization of this expensive technology process. The reasons connected with the expensive equipment used in microelectronic fabrication, the use of sophisticated materials and the long chain of sequential steps required to obtain the desired micro and nano-structures.

Nowadays the goal of EBL production process is reaching the critical dimensions of 50-150 nm [1] with the necessary quality and reproducibility of the obtained microstructures. In this region, the desired dimension of the fabricated microstructures within reasonable tolerances cannot be obtained without a deep knowledge of the process and a precise choice of processing parameters. In the sub-500 nm region, it is very important that the desired relief profile of the developed resist to be produced by a proper choice of optimal process parameter settings [2, 3].

In this work experimental investigation of exposed and developed negative electron resist AR-N 7520 profiles using EBL system ZBA23 (Raith) is performed at variation of the exposure doses and pre-defined exposure pattern. Other EBL process parameters, that influence the shape of the obtained resist profiles and are kept constant during the experiments are: electron energy, development time, initial resist thickness, etc. Several overall geometry quality criteria for the shape of the developed resist profile cross-sections are defined. Empirical models are estimated for the dependence of overall geometry characteristics of the obtained resist profiles on the exposure dose. These overall quality characteristics are used for defining of technological requirements for the produces profiles and for obtaining optimal regimes by multicriterial optimization.

2. Experimental results

The EBL process is conducted in two basic steps: exposure of the electron resist (positive, negative, chemically amplified, multilayer) by an electron beam using pre-defined pattern of exposed zones and development of the resist with an appropriate developer (depending on the resist) for production of desired microstructures.

Experiments were performed using EBL system ZBA23 (Raith) with the variable-shaped electron beam cross-section at 40 keV electron energy [3-5]. Thin film of the negative electron beam resist AR-N 7520 (Allresist) with the thickness of 480 nm was prepared by spin coating on GaAs substrate. The development was conducted with AR 300-47 developer for 60 seconds. The resist thickness measurements were carried out using the standard profilometer technique (Alphastep equipment). A high-resolution scanning electron microscope Quanta FEG 250 (FEI) was used for dimension measurements of resist profiles at the magnification of ×200 000 [5].

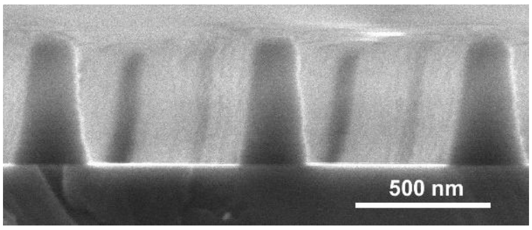

Fig. 1 *Profile of line grating with L/S 100/ 700 nm at exposure dose 340 μC/cm².*

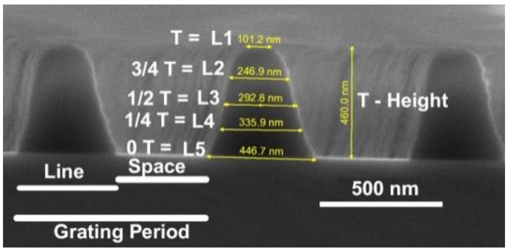

Fig. 2 *Measurement dimension details of AR-N 7520 resist profiles.*

Several single lines with a width of 100 nm and a distance between them of 700 nm are exposed with different exposure doses. After development gratings are obtained and Fig. 1 presents the obtained structure in the case of 340 μC/cm^2 exposure dose. The overall height of the profiles in AR-N 7520 resist after development is marked by T (Fig. 2) and its values are different depending on the exposure doses. The widths of the lines L_i after development were measured at different resist depths: $L_1 = T$, $L_2 = ¾\ T$, $L_3 = ½\ T$, $L_4 = ¼\ T$ and $L_5 = 0T$ (at the substrate surface) (Fig. 2) and for different exposure doses Q.

In order to investigate the influence of the exposure dose on the geometry of the developed after exposure profiles in the resist, experiments applying 13 exposure doses in the region from 250 μC/cm^2 to 470 μC/cm^2 are performed. The realized experimental points are visualized in Fig. 3. The values of the overall height T for different exposure doses (in red) and the resist thickness levels L_1 to L_5 for a given exposure dose, corresponding to one resist profile and five measurement of the obtained line width (in blue for exposure dose of 320 μC/cm^2) are presented (Fig. 3). The experiments for 250 μC/cm^2 and 320 μC/cm^2 are repeated three times. The overall number of produced structures is 17, and the performed measurements of the line widths at different resist thicknesses and exposure doses are 84.

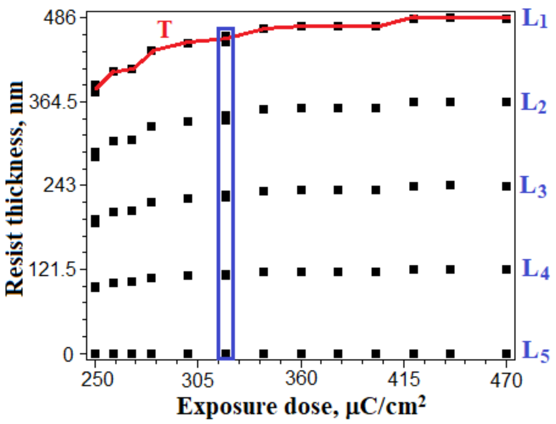

Fig. 3 *Experimental design.*

Several overall geometry quality parameters are defined: *T* – overall height of the developed resist profile, *m* - average line width at exposure with a certain dose (determined as the arithmetic mean of the individual line widths at different resist depths L_i – Fig. 2), σ – the standard deviation of the line widths obtained at exposure with a given exposure dose and δ - the difference between the line widths L_5-L_2 at resist depth 0*T* (at the resist-substrate interface) and ¾ *T*. The results concerning these parameters are presented in Table 1.

Table 1. *Overall geometry quality parameters, depending on the exposure doses.*

№	Q, $\mu C/cm^2$	T, nm	m, nm	σ, nm	δ, nm
1	250	386	110.7	53.58	83
2	260	410	135.6	66.60	86
3	270	414	146.6	66.91	77
4	280	440	154.0	67.02	93
5	300	450	180.0	66.40	93
6	320	455	204.4	72.36	82
7	340	472	216.8	75.49	93
8	360	475	219.0	75.76	94
9	380	476	228.4	83.60	122
10	400	476	257.4	122.27	233
11	420	486	290.4	152.92	316
12	440	487	359.6	259.91	564
13	470	486	377.2	274.91	603

Three repeated observations are obtained at two of the exposure doses: 250 µC/cm² and 320 µC/cm². The mean values m_i and the standard deviations σ_i of the measured line widths for a given exposure dose give an idea about the repeatability of the results. The mean line width values and the standard deviations are estimated at different resist depths: $L_1 = T$, $L_2 = ¾\ T$, $L_3 = ½\ T$, $L_4 = ¼\ T$ and $L_5 = 0T$ (at the substrate surface) and are presented in Table 2.

Table 2. *The mean line width values and the standard deviations for exposure doses of 250 µC/cm² and 320 µC/cm².*

Q, $\mu C/cm^2$	Param.	L_1	L_2	L_3	L_4	L_5
250	m_{250}	31.67	85.67	124.33	143.33	168.67
	σ_{250}	2.89	6.66	7.37	11.02	17.62
320	m_{320}	86.33	194.67	224.33	239.67	277
	σ_{320}	5.13	5.51	8.02	6.11	6

3. Regression models

Regression models are estimated for the defined overall geometry quality parameters as a function of the exposure dose coded in the region from (-1) to 1 units (*x*). The relation between coded *x* and natural units *Q* [µC/cm²] in this case can be expressed by the equation:

$$x = (Q - 360)/110. \quad (1)$$

The regression models, together with the determination coefficients values are presented in Table 3.

Table 3. *Regression models.*

	Regression models	R^2, %	R^2_{adj},%
T	$Y_T = 471.13 + 22.55x + 27.19x^3 - 35.12x^4$	98.45	97.93
m	$Y_m = 218.17 + 93.56x + 100.72x^2 + 45.24x^3 - 73.64x^4$	98.36	97.54
σ	$Y_\sigma = 71.08 + 108.58x + 210.98x^2 - 116.48x^4$	95.75	94.34
δ	$Y_\delta = 88.21 + 269.63x + 553.41x^2 - 300.67x^4$	96.87	95.83

The goodness of fit tests and the values of the determination coefficients show good prediction characteristics of the estimated models. They can be used for the choice of the exposure dose settings under given technological requirements.

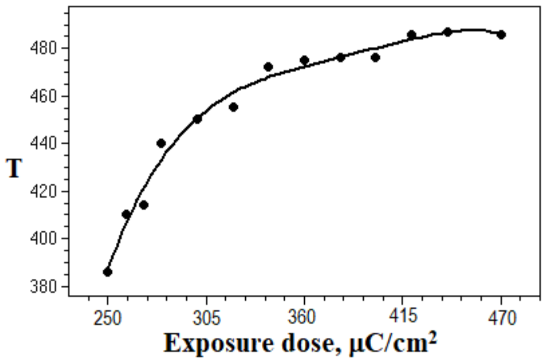

Fig. 4 *Overall height of the developed resist profile T vs. the exposure dose Q.*

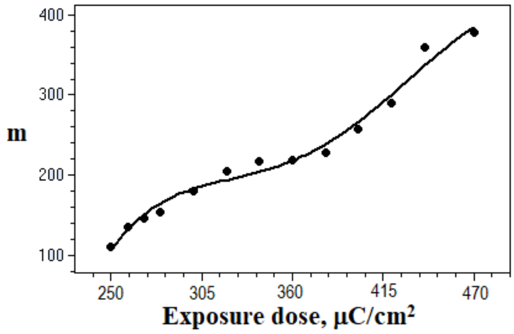

Fig. 5 *Mean line width m vs. the exposure dose Q.*

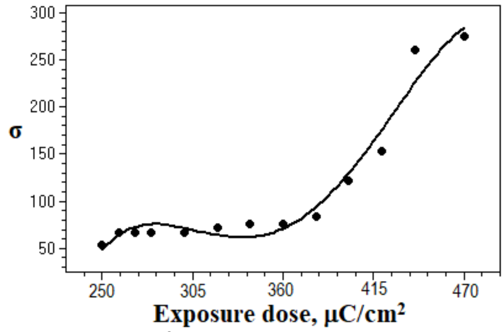

Fig. 6 *Standard deviation of the line widths σ vs. the exposure dose Q.*

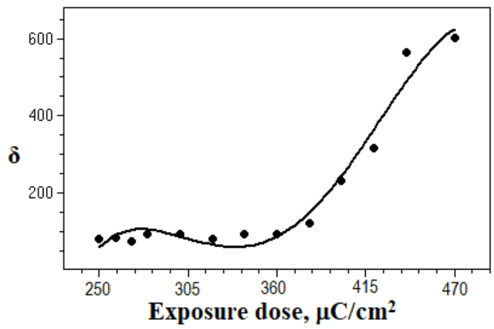

Fig. 7 *Difference δ between the line widths L_5-L_2 vs. the exposure dose Q.*

In Fig. 4 – Fig. 7 are presented plots of the experimental results (signed with dots) and the estimated by the regression models

(Table 3) for the resist profile geometry characteristics: the overall height of the developed resist profile (Fig. 4), the average line width (Fig. 5), the standard deviation of the line widths (Fig. 6), and the difference between the line widths L_5-L_2 (Fig. 7).

Based on the obtained results the following conclusions can be made:

- All the investigated overall geometry quality parameters depend on the exposure dose;
- The overall height T of the developed resist profile for the lower exposure doses (320 µC/cm^2) differs considerably from the initial resist thickness;
- The estimated regression model for the mean width of the resist profile m can be used for choosing the dose of exposure settings, depending on the technological requirements for the width of the resist profiles;
- The standard deviation of the line widths, obtained at exposure with a given dose, is connected with the variation between the line widths L_i at different resist depths and can be considered as considerable for exposure doses above 380 µC/cm^2.
- The difference between the line widths L_5-L_2 at resist depths 0T (at the substrate) and ¾ T for exposure doses below 380 µC/cm^2 can be considered as approximately constant.

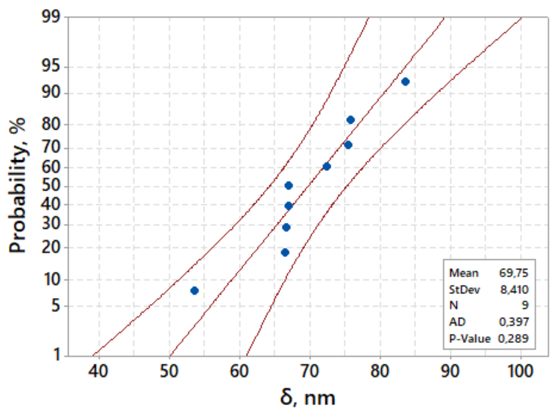

Fig. 8 *Normal probability plot for the difference δ between the line widths L_5-L_2.*

In Fig. 8 the normal probability plot for the difference δ between the line widths L_5-L_2 for exposure doses in the interval 250-380 µC/cm^2 is presented. The hypothesis test is performed by Anderson-Darling criterion and shows that the distribution is normal, since the estimated probability p = 0.289 for accepting the hypothesis is larger than the critical value p = 0.05.

This result shows that the overall criterion difference δ between the line widths L_5-L_2 is not influenced significantly by the exposure dose Q and can be estimated by its mean value $\bar{\delta}$ = 69.75 nm for the exposure dose interval 250-380 µC/cm^2. For these exposure doses the sidewalls of the developed resist profiles are most near to vertical for the resist depths between 0T (at the resist / substrate interface) and ¾ T.

4. Multicriterial optimization

The estimated in section 3 regression models give prediction for all the investigated overall geometry quality parameters when the exposure dose is set to a certain value. The multicriterial optimization task in this case is connected with the fact that under certain tolerance limits for the mean value of the linewidths (m), corresponding to a tolerance interval of the exposure doses Q, the simultaneous fulfilling of the opposite requirements for the other geometry parameters (T, σ, δ) must be done.

Since the desired optimal directions for the overall geometry parameters are different, compromise solutions should be found. By implementation of the statistical software QstatLab [6] and genetic algorithm, Pareto-optimization is realized under the following requirements:

Mean line width m: $m \rightarrow maximum$, $130 \leq m \leq 150$ nm;
Overall height of the developed resist profile T: $T \rightarrow maximum$;
Standard deviation of line widths σ: $\sigma \rightarrow minimum$;
Difference δ between the line widths L_5-L_2: $\delta \rightarrow minimum$.

Table 4. *Pareto-optimal solutions.*

№	Q, µC/cm^2	T, nm	m, nm	σ, nm	δ, nm
1	260.67	407.40	133.53	67.62	96.08
2	262.97	411.32	138.36	68.95	98.94
3	259.82	405.91	131.67	67.06	94.83
4	268.20	419.48	148.22	70.91	102.79
5	264.62	414.00	141.64	69.72	100.54
6	265.97	416.13	144.21	70.24	101.58
7	267.23	418.04	146.50	70.65	102.33
8	263.90	412.86	140.24	69.40	99.90

Part of the obtained compromise Pareto-optimal solutions are presented in Table 4. These solutions simultaneously fulfil the set of technological requirements. All the obtained optimal exposure doses presented in table 4 can be chosen, thus making compromise with the set requirements to different extend for each single case. The property of the Pareto-optimal solutions consists in the following: if each two solutions are compared, at least one of the quality parameters in one of the solutions will have worse value than that in the other solution.

5. Conclusions

This work presents experimental and theoretical investigation of exposed and developed AR-N 7520 negative electron resist profiles using EBL system ZBA23 (Raith) at variation of the exposure doses and pre-defined exposure pattern. Several overall geometry quality criteria for the shape of the developed resist profile cross-sections are defined. Empirical models are estimated for the dependence of overall geometry characteristics concerning the obtained resist profiles on the exposure dose. These overall quality characteristics are used for defining technological requirements for the formed profiles and for obtaining optimal regimes by multicriterial optimization.

The region of the exposure doses, for which the sidewalls of the developed resist profiles are most near to vertical for the resist depths between 0T (at the resist/substrate interface) and ¾ T is defined as 250-380 µC/cm^2.

Acknowledgements

The research was conducted within the framework of the project KP-06-N27/18, funded by the National Fund “Scientific Investigations”, with the support from the Bulgarian Academy of Sciences and the Slovak Academy of Sciences (Bilateral grant agreement between BAS and SAS) and from the mobility project SAS-BAS 2021-2022 of the Slovak Academy of Sciences, and from the Ministry of Education of the Slovak Republic and the Slovak Academy of Sciences under the Contract No. VEGA 2/0119/18.

References

1. K. Vutova, G. Mladenov, Microelectronic Engineering, **57-58**, 349-353 (2001)
2. E. Koleva, G. Mladenov, Vacuum, **77**, 4, 361-370 (2005)
3. E. Koleva, K. Vutova, I. Kostic, J. of Phys. Conf. Ser., **1089** (1), 012015 (2018)
4. R. Andok et al., Proc. 9th Int. Conf. ASDAM 2012 (*Smolenice, SR*) (*Piscataway: IEEE*) 287-290 (2012)
5. I. Kostic, K. Vutova, E. Koleva, A. Bencurova, A. Konecnikova, R. Andok, J. of Phys. Conf. Ser. 2021. Proc. Int conf. VEIT’21 (accepted)
6. QstatLab home page: http://www.qstatlab.co.uk/eng/index.html