Substrate Effect in Electron Beam Lithography

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Abstract. *Electron Beam Lithography (EBL) process strongly depends on the type of the applied lithographic system, composed of electron sensitive polymers and the substrate. Moreover, applied acceleration voltage changes the volume of Backscattered Electrons (BSE) participation in total energy absorption in resist layers. Proper estimation of energy distribution in used materials, due to electron scattering, is the key in final resist profile calculation and critical parameter in the designing process of the lithography exposure. In the presented paper, the Monte Carlo (MC) simulations of electron beam influence on lithographic system, consisting of positive tone resists (PMMA/MA and CSAR-62) spin coated on different substrates, will be presented. For high accuracy, obtained point spread functions were modelled by double-Gaussian function for Si, GaAs, AlGaN/GaN and InP substrates, respectively. Extracted scattering parameters of forward and backward electrons will be shown and their differences will be discussed. Results of simulated and conducted process of 100 nm metallic path fabrication on mentioned materials will be presented and compared. The practical usage of EBL technique will be shown in the aspect off low resolution application in low energy range of primary electron beam.*

Keywords

Electron beam lithography, scattering parameters, substrate effect.

1. Introduction

Electron Beam Lithography (EBL) process, due to the type of influence on the matter, suffers strongly from electron scattering. From the technological point of view, precise definition of the value of this impact is highly recommended for structures fabrication. In principle, e-beam lithography is based on electron energy transfer to the sensitive polymer, according to the designed software mask. Discrepancies between the project and the final results in polymer layer mainly come from the specific scattering, that increases the area of exposure and blurs the defined geometry of the structures. From the semiconductor technology point of view, commonly applied substrates like GaAs, Si, AlGaN/GaN or InP have huge impact on the final lithographic structures appearance. For the same exposure parameters values and used analogical resists configurations, resolution of the lithographic windows will be different for all listed materials. The main reason comes from the atomic number, Z, and the material density, ρ, of the applied substrates, that effect on the differential cross section of the electron scattering and electron mean free path, λ. This physical phenomenon is described by Mott scattering formula [1] and it is used in many scattering calculation programs. Nevertheless, the analytical study of electron scattering in lithographic exposure in combination of the above-listed substrates and selected positive tone resists (PMMA/MA and CSAR-62) is not available in the literature or any technical data sheets. Only well-known PMMA is the exception to this.

The aim of the conducted research was the definition of the technological influence of applied substrate in resist stack in structure fabrication by electron beam lithography for poorly described resists, especially for CSAR-62. We have focused on the scattering parameters change as a function of substrate material and compared them with obtained nano-metric structures resolution. Additionally, we analyzed the substrate influence on lithography process in the low-energy range of exposure as a tool for EBL efficiency improvement.

2. Monte Carlo Simulations

2.1. Substrate Material in EBL

Electron beam interaction with solid matter is easy to describe using Point Spread Functions (PSF). In this context, lithography exposure is defined as electron beam energy deposited in resist stack and the substrate, per volume unit. To estimate the total influence of the substrate material in energy absorption in the resist layers, it is more appropriate to use the area unit. Hence, we analyze the energy absorption in total thickness of resist.

In Fig. 1 and Fig. 2, PSF curves for resist materials, namely CSAR-62 and PMMA/MA on Si, GaN, GaAs and InP substrates, are presented. Obtained results come from Monte Carlo (MC) simulations (CASINO Software [2]) of single point exposures, with 20 kV acceleration voltage. To simplify the comparison of used polymers, both have similar thickness - 200 nm. The obtained energy absorption Enorm, in each case, was normalized by the total number of used electrons in MC simulation. Linear scale of PSF curves enables to expose the part of the graph, which is corresponding to long distance scattering, deriving from Backscattered Electrons (BSE). In this area, the substrate relation with energy absorption is evident, which is consistent with the theory. With higher substrate atomic number Z, the elastic scattering increases approximately with Z^2, and for this reason, more BSE electrons will come from the substrate to the resist and take part in the re-exposure. It can be seen in Fig. 1 and in Fig. 2. In Tab. 1, atomic number Z for studied materials is included. The value of Enorm increases and the curve is shifted, respectively to the value of the atomic number for studied substrates. Moreover, the total energy absorption in the resist layer (Tab. 2), integrated with respect to the distance r, in the range from 0 to 4000 nm, also proves the fundamental contribution of the substrate material in the energy transfer to the used resist [3]. Obtained values of total energy absorption between studied substrate materials show pronounced discrepancies even around 40 % for Si and InP. The energy values for each examined substrate are visibly higher for CSAR-62.

Tab. 1: Atomic numbers Z of used substrates.

	N	Al	Si	P	Ga	As	In
Z	7	13	14	15	31	33	49

More detailed analysis of substrate influence on energy absorption in resist stack should be described with the mathematical formula. For this purpose, we approximate the PSF(r) by superposition of two Gaussian functions Eq. (1), that is accurate enough for the specified goal [4].

Tab. 2: Total energy absorption in the resist layer for different substrates, for single point exposure, based on Fig. 1 and Fig. 2.

	E_{norm_total} [eV/nm]			
	Si	**GaN**	**GaAs**	**InP**
PMMA/MA	0.0044	0.0054	0.0058	0.0061
CSAR-62	0.0051	0.0064	0.0068	0.0072

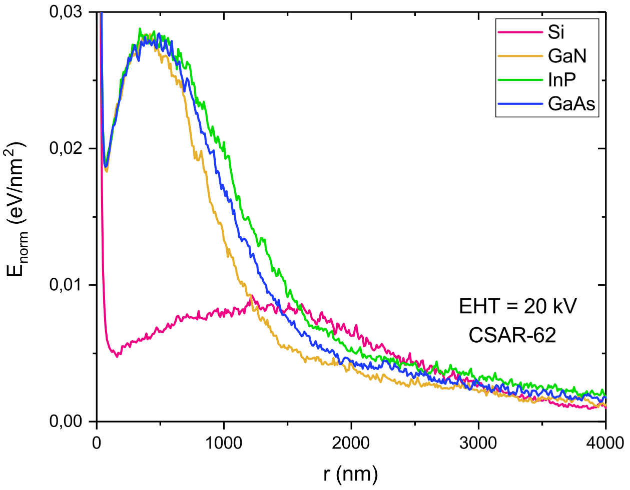

Fig. 1: Energy absorption in CSAR-62 in a function of distance from point exposure for different substrate materials.

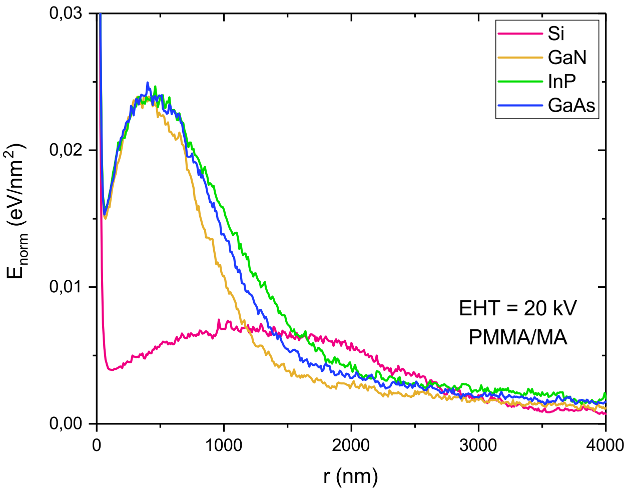

Fig. 2: Energy absorption in PMMA/MA in a function of distance from point exposure for different substrate materials.

$$\mathrm{PSF}(r) = \frac{1}{\pi(1+\eta)} \cdot \cdot \left[\frac{1}{\alpha^2} \exp\left(-\frac{r^2}{\alpha^2}\right) + \frac{\eta}{\beta^2} \exp\left(-\frac{r^2}{\alpha^2}\right) \right]. \tag{1}$$

In this equation, the α represents the forward scattering range, the parameter β represents the backscattering range and the η is the ratio of the backscattered energy level to the forward-scattered energy level. The results of the conducted calculations are collected in Tab. 3 and Tab. 4 for CSAR-62 resist and for

PMMA/MA resist, respectively, for each examined substrate. With substrate atomic number Z increase, the β and η also increase, while the α is almost the same for each case. This must be taken into consideration during the EBL process design.

Tab. 3: Scattering parameters values, calculated for CSAR-62, for EHT = 20 kV.

CSAR-62	α	β	η
Si	13 nm	98 nm	0.000002
GaN	15 nm	152 nm	0.00002
GaAs	14 nm	213 nm	0.00003
InP	12 nm	280 nm	0.00006

Tab. 4: Scattering parameters values, calculated for PMMA/MA, for EHT = 20 kV.

PMMA/MA	α	β	η
Si	12 nm	97 nm	0.000002
GaN	16 nm	183 nm	0.00002
GaAs	14 nm	223 nm	0.00004
InP	13 nm	562 nm	0.0003

2.2. Acceleration Voltage Parameter in EBL

Acceleration voltage (EHT) in the e-beam techniques plays huge role in the volume of interaction between the primary beam and the used material. In the lithography process, it is one of the principal technology parameter, which determines the final result of structures fabrication. Increasing the value of EHT causes the interaction extends to the deeper region of the substrate. From lithographer point of view, it reduces the BSE scattering and allows to obtain truly high resolution of fabricated patterns. At the same time, only a small part of the initial energy is consumed for lithography purposes. The PSF curves for selected resist systems for different values of acceleration voltages are presented in Fig. 3, Fig. 4, Fig. 5 and Fig. 6.

In the graphs, we can observe the same tendency for each lithographic system. Below 10 kV, shape of the PSF curves flattens and approximation by double-Gaussian function is not precise enough. Problem grows with lowering the EHT value.

Application of the low-energy beams to lithography technique enables to achieve higher process throughput, due to the better consumption of applied energy to the primary beam. The influence of the substrate material on this energy absorption in resist layer is correlated with the depth of e-beam penetration into the resist. To achieve benefits from BSE scattering in this case, resulting in re-exposition of the resist layer, the total thickness penetration of the polymer by e-beam must be provided.

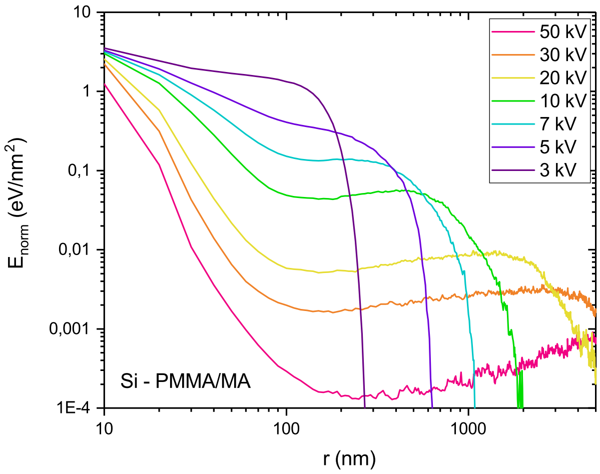

Fig. 3: Energy absorption in Si-PMMA/MA in a function of distance from point exposure for different acceleration voltages.

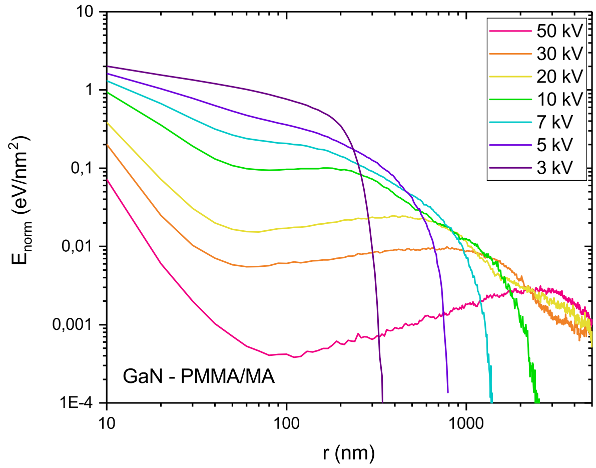

Fig. 4: Energy absorption in GaN-PMMA/MA in a function of distance from point exposure for different acceleration voltages.

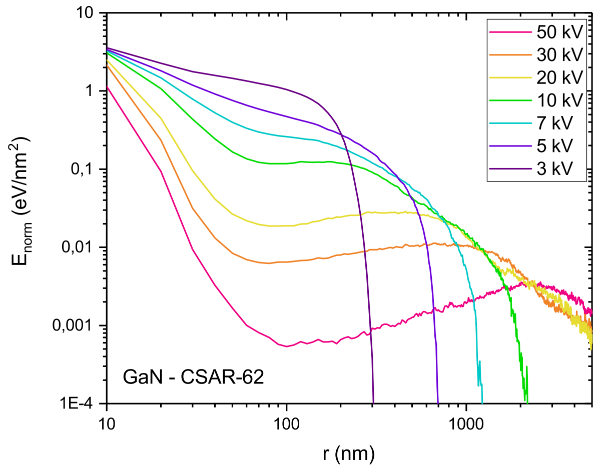

Fig. 5: Energy absorption in GaN-CSAR-62 in a function of distance from point exposure for different acceleration voltages.

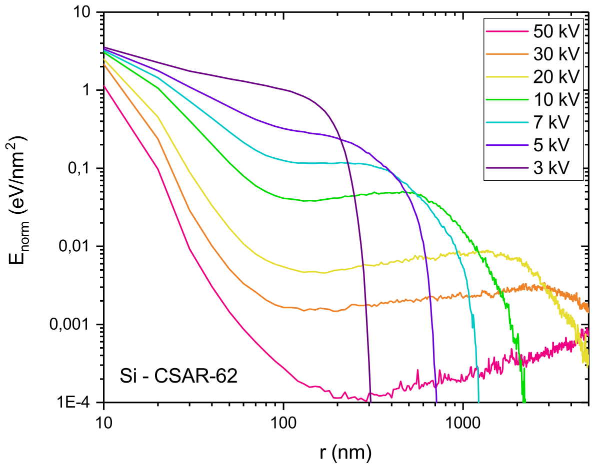

Fig. 6: Energy absorption in Si-CSAR-62 in a function of distance from point exposure for different acceleration voltages.

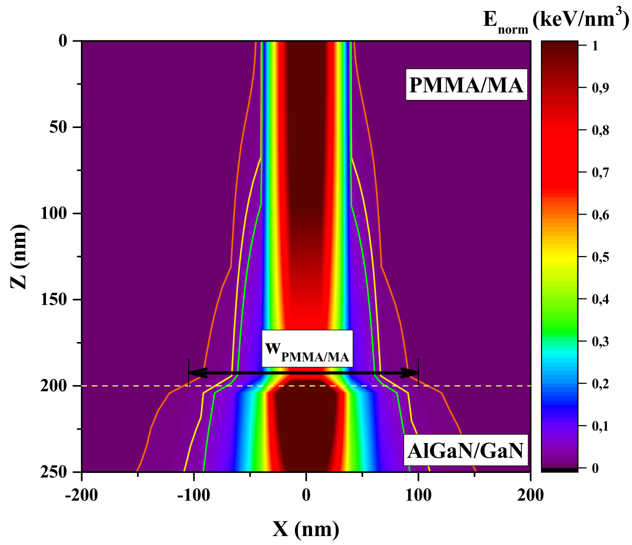

Fig. 7: Profile of energy absorption in AlGaN/GaN-PMMA/MA for 100 nm stripe fabrication, for EHT = 20 kV.

3. E-Beam Exposure of Nanometre Structures Fabrication

The energy absorption profiles of 100 nm wide stripes in 200 nm thick resist, spun on different substrates, were studied. The exemplary energy absorption profiles in PMMA/MA on AlGaN/GaN substrate are presented in Fig. 7. In green, yellow and orange lines the constant energy absorption areas are highlighted for normalized (by used electron numbers) values that are as follows: 0.1 eV/nm^3, 0.3 eV/nm^3, and 0.5 eV/nm^3. The simulated widening in the resist layer w, in the close connection to the substrate area, for mentioned energy absorption values, are presented for CSAR-62 and PMMA/MA in Fig. 8 and Fig. 9. Obtained results indicate, that the window widening $w_{CSAR-62}$ and $w_{PMMA/MA}$ is in the range of ~ 30 nm $\div$ 135 nm for both resists and strongly depends on substrate materials. It was observed that in the extreme situation, it could cause the reduplication of the designed stripes width.

Obtained simulation results are in a good agreement with calculated scattering parameters, for total thickness of resist layers and for different substrates. The best resolution (smallest window widening) was received for the lightest substrate - Si, what is confirmed by β values. Also, the value of η confirms the best fabrication conditions for Si. Differences in scattering parameters values between the PMMA/MA and CSAR-62 come from chemical composition of the resists. Therefore, the α and β values for CSAR-62 are a little bit lower than for PMMA/MA. Partial confirmation of this can be found in the graphs presented in Tab. 2. In real structures fabrication process the resistivity of the resist material on selected developers must be considered. For the PMMA resist, the energy density threshold range leads to 6.8 – 24.0 eV/nm^3 [5]. Unfortunately, similar values for the PMMA/MA and CSAR-62 are not available. We can only assume, from the values of dose to clear, that it would be lower than for the PMMA. A comparison between the PMMA and CSAR-62 has been made e.g. in [6].

As was mentioned before, changing the EHT into the higher values provides the limitation of the influence of BSE scattering from the substrate on exposure. As a consequence, it improves the pattern resolution. Obtained results are in good agreement with the literature data [7].

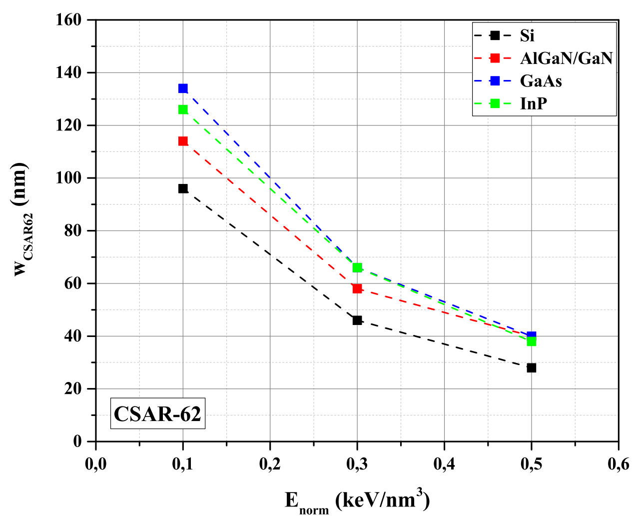

Fig. 8: Dependence of simulated widening of the exposed area of CSAR-62 in a function of absorbed energy density for different substrates.

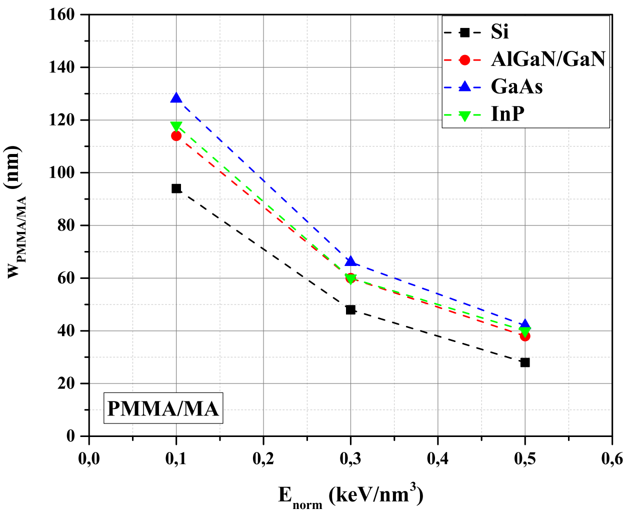

Fig. 9: Dependence of simulated widening of the exposed area of PMMA/MA in a function of absorbed energy density for different substrates.

4. Low-Energy E-Beam Lithography

Usage of low-energy electron beam for lithographic purposes reduces the resolution of the technique strongly. Nevertheless, it provides better utilization of beam energy, what was discussed in Sec. 2. In Fig. 10, cross sections of energy absorption in selected depths in CSAR-62 on GaN substrate, for 500 nm path fabrication, are presented. Due to the fact that EHT is high, the energy absorption is relatively uniform and provides good reconstruction of the pattern design. In Fig. 11, analogous resist system was simulated for lower EHT value. Results of energy absorption strongly differ from previous one. Energy absorption is substantially higher and additionally, the natural undercut was obtained in the resist layer, which can be potentially used for lift-off metallisation.

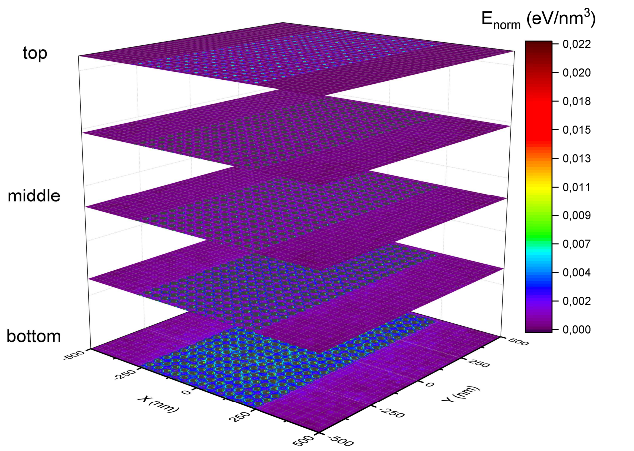

Fig. 10: Energy absorption in selected depths in CSAR62 layer on GaN substrate for EHT = 20 kV.

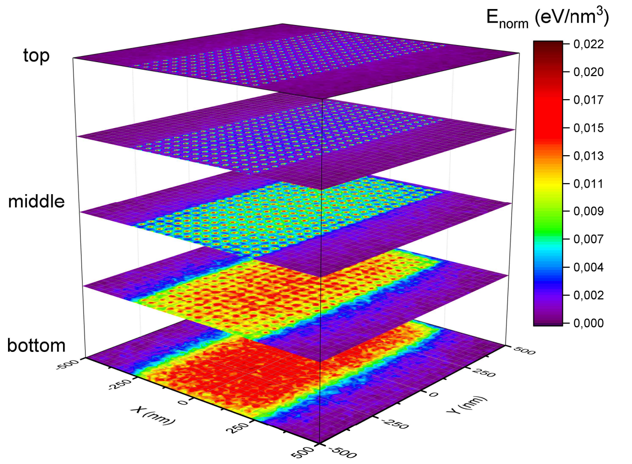

Fig. 11: Energy absorption in selected depths in CSAR62 layer on GaN substrate for EHT = 7 kV.

In Fig. 12, four graphs contain collection of two lithographic process parameters, EHT and E_{norm}, and related to those two, window horizontal dimension w (based on MC simulations). Magnification of the acceleration voltage distinctly reduces the energy utilization for polymer modification but provides minor widening of the pattern (Fig. 12(d)). Low-energy lithography enables to use majority of applied energy for pattern fabrication at the expense of loss of high resolution and possibly not properly expose the deeper areas of resist (Fig. 12(a)). Middle values of EHT (Fig. 12(b) and Fig. 12(c)) give the opportunity to enhance the efficiency of EBL in big scale exposures.

5. Conclusion

In the paper, the variation of PSF curves of energy absorption in CSAR-62 and PMMA/MA layers, applied on different substrates, was presented. The dependence of achieved simulation results on applied acceleration voltages and substrate atomic number Z was discussed for single point exposures and sub-nanometre pattern fabrication. The difference in energy absorption in resist layers, dependent only on a substrate material, can amount even 40 %. An increase of the e-beam energy reduces the substrate influence in lithography process.

Based on conducted simulation results, we notice the difference in energy absorption between CSAR-62 and PMMA/MA, for the same substrates. In that case, we believe that main contribution in scattering parameters variation, β and η, comes mostly from substrate material. Lowering the EHT results in significant qualitative and quantitative modification of exposure, what can be seen in BSE scattering range reduction and substantial changes in energy profile absorption. Huge impact of material substrate in e-beam lithography and BSE scattering in resist layer can be utilized in big scale

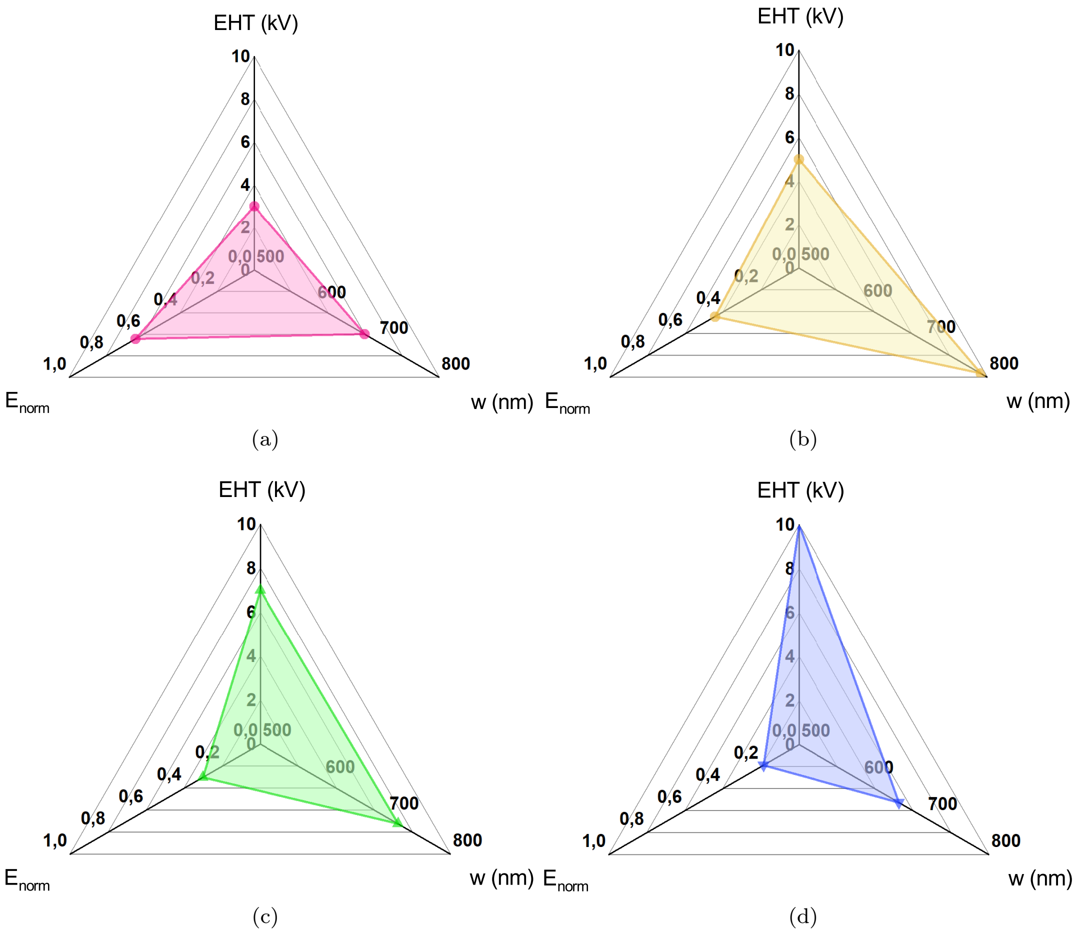

Fig. 12: Dependence of electron beam lithography parameters and window dimensions in CSAR-62 layer on GaN substrate.

exposures, as a beneficial effect. In this low-resolution mode of EBL, we profit in increasing of process performance.

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