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Exposition time analysis of AlGaN/GaN HEMT fabrication by electron beam lithography

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Electron beam lithography, due to the high design flexibility and high pattering resolution can be used as an exclusive lithography method in device fabrication in R&D reality. To achieve the reasonable time of process exposition, some essential steps and actions must be done. In the article, the main technical and technological dependences, based on AlGaN/GaN HEMT transistor fabrication, will be presented and discussed. As a result of conducted studies, the total time of the most important lithography process expositions will be shown and explained.

Keywords: electron beam lithography, device fabrication, exposition time reduction.

1. Introduction

Semiconductor device manufacturing contains several technological and testing steps before it can be ready for packaging. Device, like high electron mobility transistors (HEMT), in the very basic layout, demands minimum five lithography processes, which can be doubled or even tripled for devices with sophisticated design. Based on the industrial reports, lithography processes can absorb even one-third of the total costs of the large scale fabrication. On the other hand, current lithography expectations are focused at the same time on extremely high resolution and high throughput from large areas of substrate. There is a strong relationship between generated costs of lithography processes and the resolution or accuracy of copied structures. One of the reasons is the equipment cost, which is one order of magnitude higher for deep ultraviolet (DUV) systems and two orders of magnitude higher for extreme ultraviolet (EUV) systems than for electron-beam lithography (EBL) or i-line photolithography systems [1]. At the same time, the resolution of the EBL technique and EUV technique is comparable, where DUV technique provides one order of magnitude lower resolution.

Despite the fact of high resolution and undistinguished equipment costs of EBL, it is not used in mass production because of very low yield, which is the lowest from previous mentioned methods. Nevertheless EBL is commonly used in research laboratories and pre-commercial production lines, where total time of exposition does not have to be compensated in total costs of device fabrication.

Utilization of EBL in pilot line production requires some modifications and optimization in order to minimize the total time of exposition from days to hours.

2. Reduction of the exposition time

There are few ways that can be done to improve the total time of exposition. One of the most promising and the most effective is to use a new concept of the exposition method, which is based on the multielectron beam system [2]. Another way that does not require specialized equipment, propose using thinner layers of e-beam sensitive layers [3] and lower acceleration voltages [4], both improve energy absorption in a resist layer. Applying special strategies of substrate scanning and, if possible, reducing the area of exposition, also help with time reduction.

In our research we focused on minimization of dwell time T_{dwell} according to the following equation for the area dose:

$$\text{Area dose} = \frac{I_{\mathrm{beam}} \cdot T_{\mathrm{dwell}}}{\mathrm{ASS} \cdot \mathrm{ASL}}$$

Increasing the value of the beam current I_{beam} and adjusting the area step size ASS and the area step line ASL to possibly big values, can distinctly improve the yield of lithography process.

3. Experiment

Conducted experiments refer to the most demanding lithographic steps in AlGaN/GaN HEMT fabrication: mesa formation, ohmic contact and Schottky contact formation

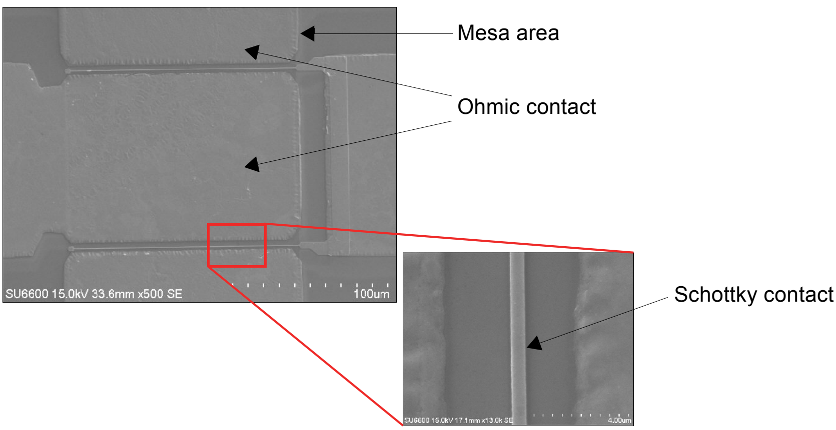

Fig. 1. SEM image of the AlGaN/GaN HEMT with the magnification on gate area.

T a b l e. Resist materials with their nominal doses used for conducted AlGaN/GaN HEMT fabrication, for selected EBL processes, with information about the area of exposition. All information refers to the single device fabrication.

	Resist material	Nominal dose [μC/cm^2]	Area [μm^2]	Importance of resolution
Mesa	CSAR 62	65	~190 000	+
	AR-7520	30	~80 000	+
	PMMA/MA	33	~190 000	+
Ohmic contact	PMMA + PMMA/MA	100	~160 000	++
Schottky contact	PMMA + PMMA/MA	100	~15 000	+++

(Fig. 1). Based on those three EBL processes, we calculated the time exposition ranges in which full process fabrication of a device can be executed.

Exposition time analysis was done for AlGaN/GaN/Al_2O_3 HEMT types heterostructures in each process for different resist materials and an area size of exposition. Experiments were conducted on PIONEER (Raith) equipment. Despite of the exposition time reduction, great importance was attached to obtained high resolution of structures and high quality of lithography process. In the Table, the applied resist materials with their dedicated nominal doses and the area sizes of exposition for each lithography process are presented.

As the main parameter in conducted studies was selected the beam current I_{beam}, which can be increased no-directly by magnification of the aperture size ϕ. Additional slight current increase can be achieved by changing the e-beam energy into higher values. The first method causes e-beam defocusing on the sample and as a consequence, the loss of high resolution for bigger apertures. The second idea is strongly connected with energy absorption efficiency in the resist layer, and as a consequence, proper dose -to-clear must be modified for each process parameter set. Applying a higher EHT value reduces backscattering effects, which improves structures resolution, what is beneficial for gate fabrication.

Experiments were done for 3–30 kV acceleration voltages with the use of an aperture size ϕ: 7, 15, 30, 60, and 120 μm.

4. Discussion

Mesa structure definition in EBL process is not a demanding step from the structures resolution point of view. Therefore, applying big size apertures is adequate in a range of currents values, which are relevant to the used nonconductive substrate and the charging effect can be avoided. In Fig. 2, characteristics of time exposition t as a function of applied beam current I in EBL process, for mesa structure fabrication, for two designs: positive (CSAR 62) and negative (AR-N 7520) layouts, are presented. The usage of $\phi = 60$ μm aperture size, which allows to work with ~1.5 nA, gives the time exposition, for presented resists, equal to single minutes for one AlGaN/GaN HEMT device fabrication and prevents the surface charging occurrence.

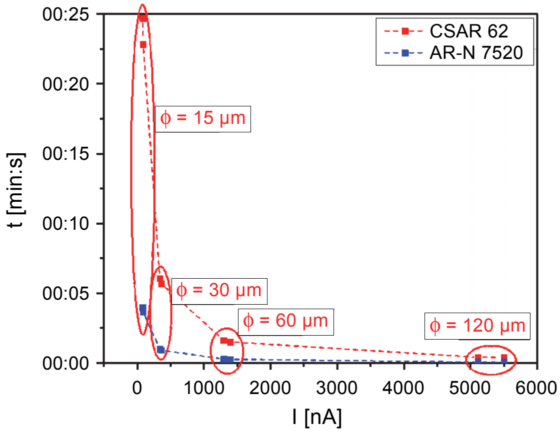

Fig. 2. Exposition time t as a function of primary electron beam current I for mesa structure fabrication, for different EHT values and aperture sizes ϕ: 15, 30, 60, and 120 µm.

Analogous tests were performed for ohmic contact fabrication. Due to the fact of bilayer resist system usage for lift-off purposes, the process is more demanding because the geometry and structures dimensions play an important role in device performance. For that reason, the analysis of time exposition was done for a wide range of electron beam current values. Results were divided into two separated characteristics, Figs. 3 and 4. Based on our previous published results [5], the best quality of fabricated ohmic structures provides the usage of one of two parameters sets: EHT = 10 kV and ϕ = 60 µm or EHT = 10 kV and ϕ = 30 µm. For a bigger aperture, the probe current I is about 0.9 nA and the time of exposition t is about 3 min, Fig. 4.

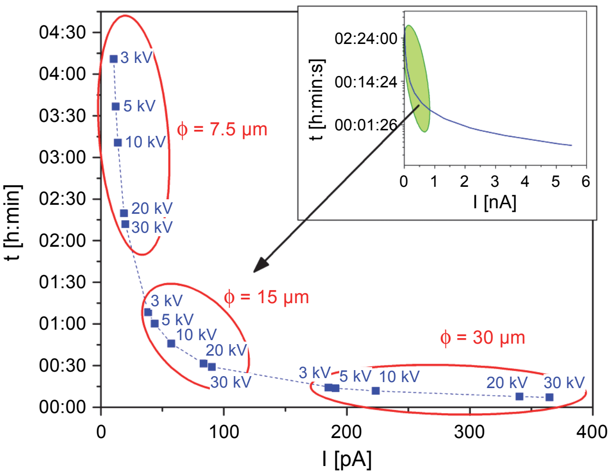

Fig. 3. Exposition time t as a function of primary beam current I for ohmic contact fabrication, and aperture sizes ϕ: 7.5, 15, and 30 µm.

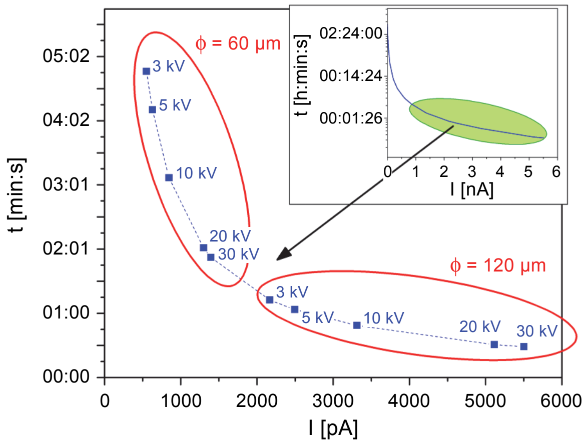

Fig. 4. Exposition time t as a function of primary beam current I for ohmic contact fabrication, and aperture sizes ϕ: 60 and 120 μm.

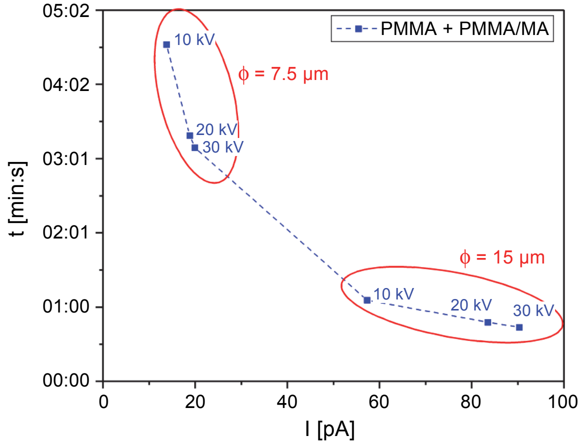

Fig. 5. Exposition time t as a function of primary beam current I for Schottky contact fabrication, for different aperture sizes ϕ: 7.5 and 15 μm.

Applying a smaller size of the aperture ϕ, equal or below 30 μm, shifts the time of exposition to single hours (Fig. 3), what is more adequate to Schottky contact fabrication, because of the fact of high precision and resolution of direct writing.

In Fig. 5, the time exposition characteristics as a function of e-beam current I, for the smallest aperture size ϕ = 7.5 μm and ϕ = 15 μm are presented. Results refer to I–type Schottky contact, whose length was equal to 500 nm. Fabrication of shorter gates, in the same resist system, requires higher doses values, and the exposition time in that situation must be recalculated [6]. Exposition time for a single HEMT device was in the range from about 0:45 to 4:30 (min:s).

5. Conclusions

Conducted experiments, for three most characteristic and demanding EBL steps in the fabrication process of AlGaN/GaN/Al_2O_3 HEMT, allow us to approximate and verify the total time of resist exposition by EBL, including all six lithographies needed for device production. Basing on the capabilities of obtaining comparable technological results of the lithography process, for different technological parameters sets and different electron beam sensitive materials application, the final results can be executed in a wide range of exposition time values. The greatest flexibility of time fabrication can be achieved for ohmic contact fabrication, and as a consequence, for a metal thickening process. The exposition time in this situation can be in the range from 2:00 to 10:00 h:min. We obtained very similar results for mesa structure fabrication process. Including two types of mask and three resists materials that can be used for this process, the exposition time was in the range from 2:00 to 8:30 h:min.

For a substrate area in which 64 AlGaN/GaN HEMT transistors were fabricated, the minimum total time of EBL exposition was estimated to be 10:00 h:min.

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References

[1] Engstrom D.S., Porter B., Pacios M., Bhaskaran H., *Additive nanomanufacturing – A review*, Journal of Materials Research **29**(17), 2014, pp. 1792–1816, DOI: 10.1557/jmr.2014.159.

[2] Rio D., Constancias C., Martin M., Icard B., van Nieuwstadt J., Vijverberg J., Pain L., *5 kV multi-electron beam lithography: MAPPER tool and resist process characterization*, Journal of Vacuum Science and Technology B **28**(6), 2010, article ID C6C14, DOI: 10.1116/1.3517664.

[3] Manfrinato V.R., Cheong L.L., Duan H., Winston D., Smith H.I., Berggren K.K., *Sub-5 keV electron-beam lithography in hydrogen silsesquioxane resist*, Microelectronic Engineering **88**(10), 2011, pp. 3070–3074, DOI: 10.1016/j.mee.2011.05.024.

[4] Lee Y.-H, Browning R., Maluf N., Owen G., Pease R.F.W., *Low voltage alternative for electron beam lithography*, Journal of Vacuum Science and Technology B **10**(6), 1992, pp. 3094–3098, DOI: 10.1116/1.585935.

[5] Indykiewicz K., Paszkiewicz R., Paszkiewicz B., *Improvement of the electron beam lithography contact pads fabrication process*, Optica Applicata **46**(2), 2016, pp. 249–254, DOI: 10.5277/oa160209.

[6] Indykiewicz K., *Zastosowanie litografii elektronowej do wytwarzania tranzystora AlGaN/GaN HEMT*, PhD Thesis, Wrocław University of Science and Technology, 2018 (in Polish).

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