Proximity Effect in Gate Fabrication Using Photolithography Technique

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Abstract. *In the paper the technological factors influencing test structure gate length were described. The influence of test structure gate placement (Schottky metallization between ohmic contacts, on mesa and on GaN surface) was analyzed and discussed. Moreover, various distances between ohmic contacts paths were tested. Except for experimental investigations, simulations using finite elements method in COMSOL were performed for the same structure. The modelling results revealed crucial impact of a gap beyond the mask on the electric field distribution in photoresist layer. The smallest value of relative error of test finger lengths was observed for finger parts placed between ohmic paths on mesas. It was explained by thicker lift-off double layer between ohmic paths and the smallest Y-gap compared to test fingers placed on mesa and outside of it. Simulation did not bring an explanation of larger values of relative error for smaller distance between ohmic paths.*

Keywords

AlGaN/GaN transistors, h-line lithography, proximity effect.

1. Introduction

Continuous increase of scale of integration of electronic devices cause that the optical lithography faced its resolution limitation of used wavelength. According to Rayleigh's equation, enhancement of resolution could be assured by decrease of wavelength or higher numerical aperture of lens systems [1]. To obtain higher resolution, the wavelength was decreased from G-line (435 nm) to I-line (365 nm), further to 248 nm (excimer laser source with KrF) and to 193 nm (ArF) [2] and [3]. Also 8 various methods of image formation have been developed e.g. phase shifting method [1] and [2]. Moreover, there are efforts of development of superlenses [4], extreme ultraviolet and beyond extreme ultraviolet lithography [5], surface-plasmon polariton resonance [6].

Additionally, constants depending on resist material, process technologies and image formation techniques play an important role. The proximity effect defined as a variation in pattern width due to proximity of other nearby features is well known for electron-beam lithography [7]. The optical proximity effect was studied referring to features typical for transistors fabrication. In the paper the technological factors influencing test structure gate resolution were described. The influence of test structure gate placement was discussed. Observed phenomena were analyzed also based on computer simulations results.

2. Experimental Details

The dedicated test structures were made during AlGaN/GaN HEMT (High Electron Mobility Transistor) devices fabrication. The AlGaN/GaN heterostructures fabrication in metal-organic vapour phase epitaxy technique was described elsewhere [8]. Each transistor in the module on the wafer consisted of two test structures that differed in designed distance between ohmic contact paths:

- type 1 - designed distance of 3 µm plus designed length of test finger,

- type 2 - designed distance of 4 μm plus designed length of test finger).

Both types of dedicated test structures contained six fingers of various lengths in purpose of indirect analysis of gates lengths and chosen factors influencing its value. The designed fingers lengths were #1 – 0.6, #2 – 0.8, #3 – 1, #4 – 1.4, #5 – 2, #6 – 5 μm, respectively.

Additionally, the test structures embrace three different areas on which the test structures fingers were placed Fig. 1:

- area A - Schottky metallization on mesa between ohmic contacts,
- area B - Schottky metallization on mesa,
- area C - Schottky metallization on GaN surface (outside of the mesa).

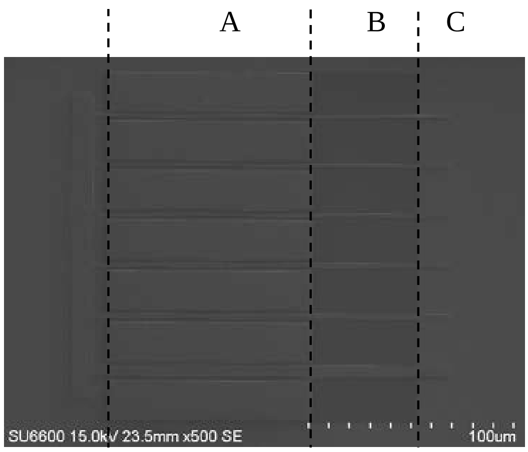


Fig. 1: SEM image of test structure.

The dedicated test structures were fabricated in AlGaN/GaN heterostructures by photolithography technique using Carl Suess MA56 mask aligner working in h-line mode. Mesas were etched through the SiO_2 mask (300 nm thick, deposited by plasma-enhanced chemical vapor deposition) in Reactive Ion Etching (RIE) system. For the RIE process a Cl_2:BCl_3 mixture of gasses was used. Time of etching equal to 70 s gave heights of mesas in the range from 70 to 87 nm. Metallization contacts were deposited in UHV system by thermal and e-beam evaporation. The metallization stack of Ti/Al/Mo/Au thermally formed in rapid thermal annealing system (at 820 °C for 60 s) was used as ohmic contact. Schottky contacts were of Ru/Au (30/150 nm) double layer.

Mesa structures patterns were made in standard lithography (using Microposit S1813 Photo Resist - Shipley) while ohmic and Schottky contacts were fabricated in lift-off technology using double layer - Shipley Microposit LOL 2000 and Megaposit SPR 700 – 1.0 (DOW). Pattern was transferred from chromium mask in vacuum contact (the vacuum seal inflates to form a chamber between mask and sample, which is then evacuated). The wavelength of exposure UV light was 405 nm and its intensity of 18 mW·cm^{-2}. The pre-bake time, time of exposure, LOL2000 and S1813 thicknesses, time of development as well as ultrasounds power during development were optimized for HEMTs gates fabrication. Additionally, step of edge bead remove to minimize the distance of the mask and sample during exposure was applied.

Fingers lengths of test structures were measured within a series of samples made in similar environmental conditions of lithography process. The yield of each sample exceeded 90 %. The lengths were measured repeatedly near the middle of each finger based on Scanning Electron Microscope (SEM) images.

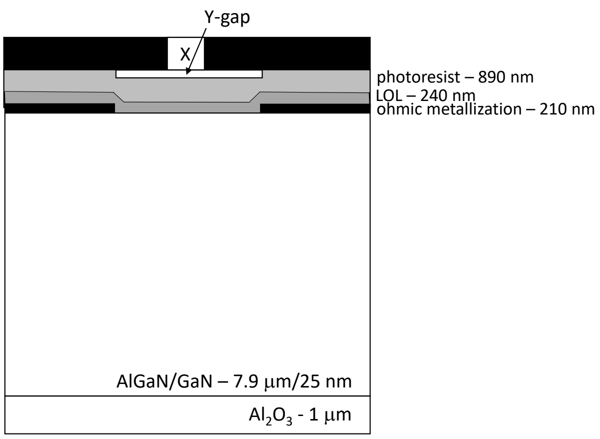


Fig. 2: The structure used for simulations in COMSOL.

Qualitative analysis of the electric field distribution in the Y-gap, photoresist and LOL (Fig. 2) during exposing was performed based on simulations using Finite Element Analysis (FEA) by COMSOL - the commercial software. The structure used for simulations was similar with that obtained in experiments. It contains (top-down):

- mask, with chromium areas and the X-gap (width as designed test finger length) - filled with vacuum during exposure,
- Y-gap, resulting from non-uniform spin coating of the photoresist due to ohmic contacts presence on the AlGaN/GaN surface - filled with vacuum during exposure,
- photoresist and LOL layer,
- ohmic metallization paths placed in the distances as in experiments (i.e. 3 and 4 μm plus designed gate length, depending on type of the structure),
- AlGaN/GaN structure.

The exposure parameters of vertically incident light in simulations were the same as for experimental part of the investigation. In the Tab. 1 the refractive index values of used materials for 405 nm wavelength are shown.

Tab. 1: Refractive index values of used materials.

SPR 700	LOL 2000	Al_2O_3	AlGaN	GaN	Glass	Metallization
1.7	1.6	1.76	2.25	2.55	1.5	1.52

3. Results

In the first step the mean value of fingers lengths in three areas was estimated (Fig. 3). Additionally, the standard deviation was calculated. Its value was the smallest for fingers parts located between the ohmic contacts pads. Standard deviations of lengths of fingers designed for 1 μm, as gate length of HEMT structures, were similar.

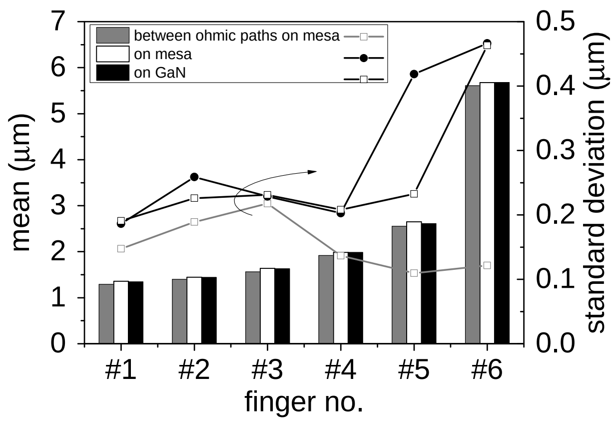
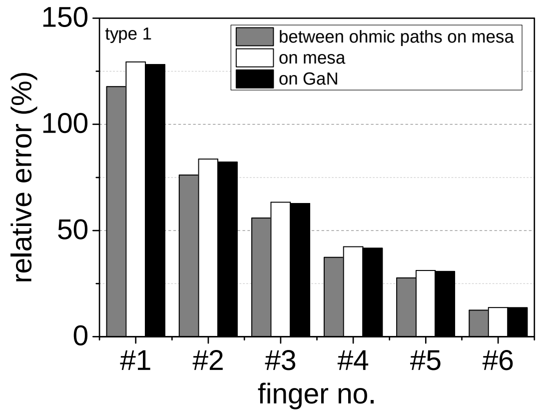


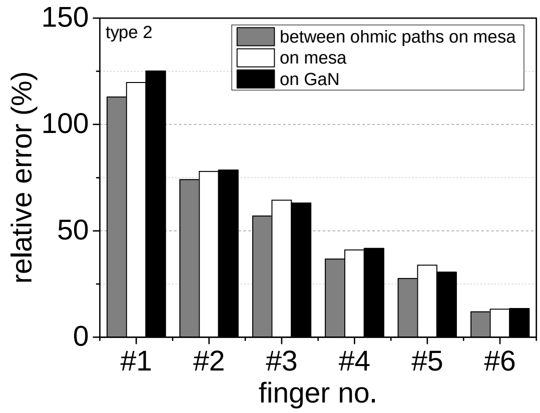
Fig. 3: Mean values and standard deviation of finger lengths of test structures.

The relative error of fingers lengths placed on three areas for both types of test structures is presented in Fig. 4(a) and Fig. 4(b).

The smallest value of relative error was obtained for finger parts placed between ohmic paths on top of mesas for structures of type 1 (depicted as area A in Fig. 1) as well as type 2 (depicted as area B in Fig. 1). Due to large height of ohmic contacts (Fig. 5) compared to lift–off double layer height the reflection on the metallization slope and its irregularities was expected to lengthen the fingers. The observed fingers length could be a consequence of thicker lift-off double layer between ohmic paths. The thicker lift-off double layer is an effect of the spin-off technique used for samples coating by resists. The time of exposure as well as time of development was equal for whole sample thus thicker layer of resists could give shorter fingers. For fingers #1, #2 and #3 observed length was larger for parts placed on GaN surface compared to those placed on top of mesa. Lengthening of fingers within this area could be caused by reflecting of exposure UV-light on whiskers that occurred on GaN surface and further exposure of patterns Fig. 6.



(a) Type 1.



(b) Type 2.

Fig. 4: Relative error of fingers lengths placed on three areas for both types of test structures.

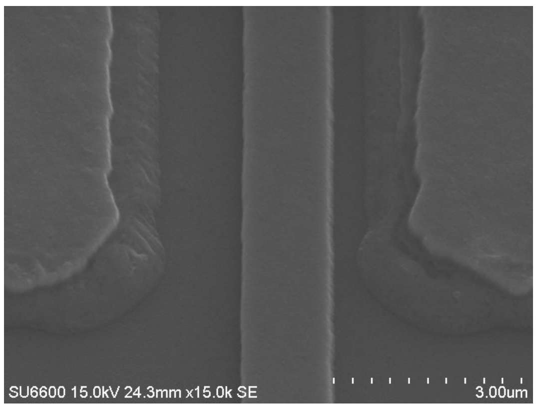


Fig. 5: SEM image of test structure finger between ohmic contacts paths.

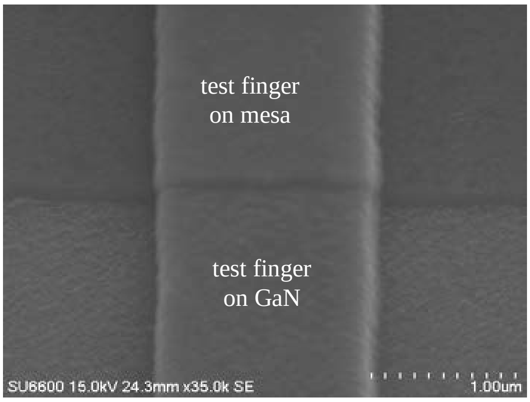


Fig. 6: SEM image of test structure finger on various areas.

The relative error of test structures fingers lengths (Fig. 7) indicated affection of ohmic contact paths distance on the lengths.

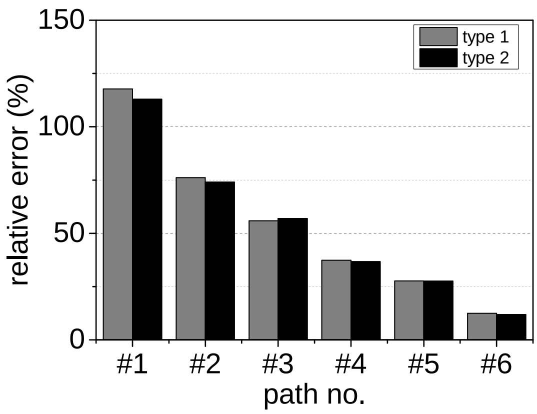
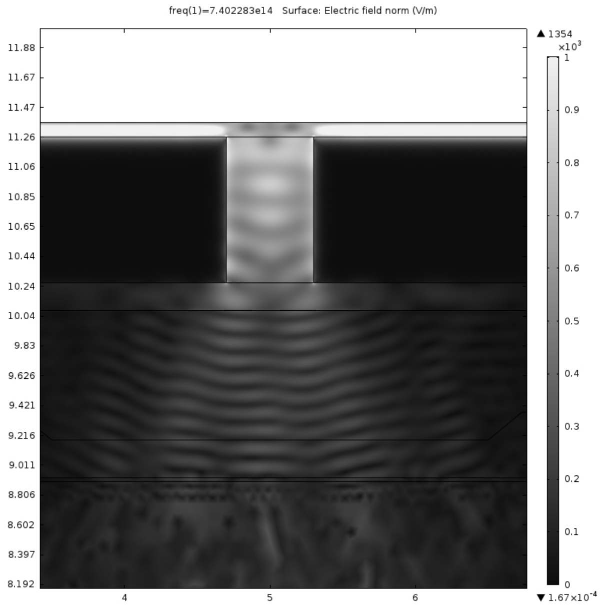


Fig. 7: The relative error of test structures fingers lengths for various ohmic contact paths distance.

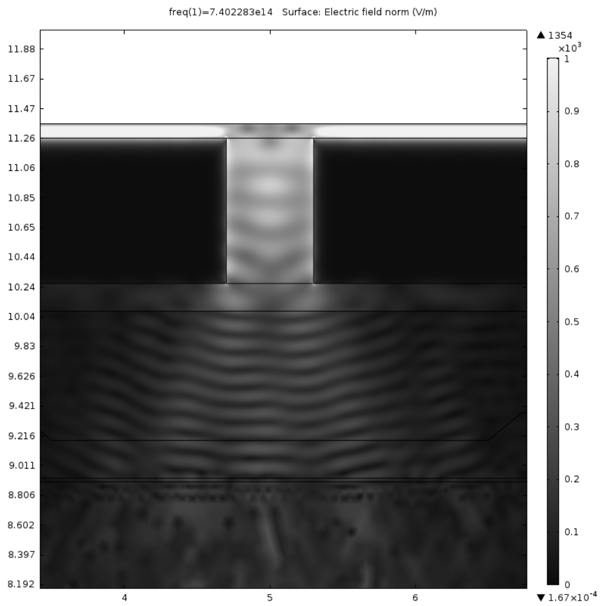
Larger values of relative error were observed for smaller distance thus influence of UV-light scattering on ohmic contacts slopes could not be excluded. As a result of the simulations the electric field distribution in the structure was obtained. Only the issue of three designed finger lengths (i.e. 0.6 μm, 1 μm and 5 μm) were selected to further discussion. The case of the smallest designed finger length (0.6 μm) for both distances between ohmic contacts paths is presented in Fig. 8.

Additionally, electric field profiles in horizontal lines in four boundaries regions were estimated. The lines were located between:

- I - mask and photoresist layer or Y-gap,
- II - LOL and ohmic contact surface,
- III - ohmic contact and AlGaN/GaN,
- IV - under the Y-gap.



(a) 0.6 μm and 3.6 μm.

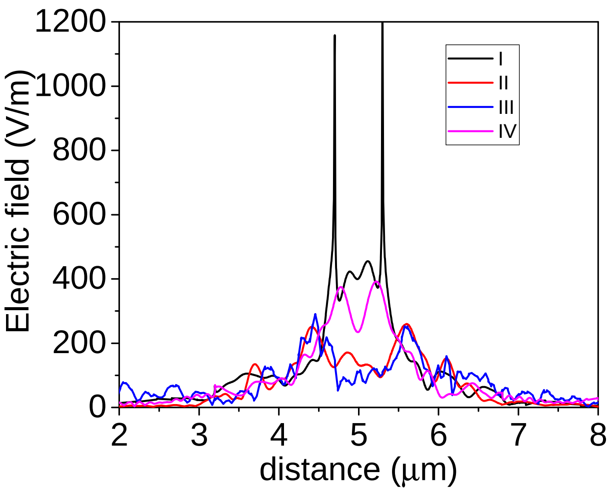


(b) 0.6 μm and 4.6 μm.

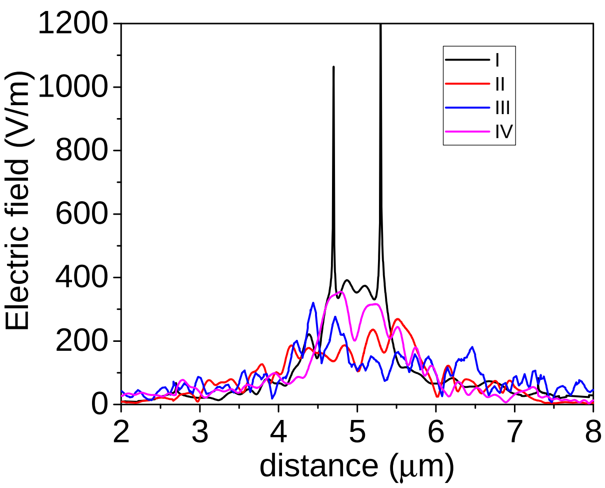
Fig. 8: Electric field distribution in structure for designed finger length and distance between ohmic contacts as depicted ($f = 7.402283 \cdot 10^{14}$, surface: Electric field norm (V/m)).

The electric field profiles for designed finger length and distance between ohmic contacts 0.6 μm and 3.6 μm in Fig. 9(a) and 0.6 μm and 4.6 μm in Fig. 9(b).

The analysis of profiles indicated expected diffraction on the edges of the chromium layer corners. The shadowing region for both cases was not evident as well as scattering on the ohmic contacts paths surfaces. A significant influence of Y-gap presence on the electric field distribution c ould be also observed for the investi-

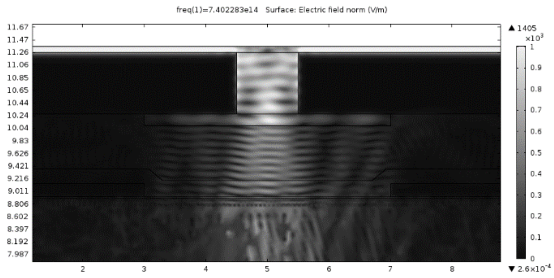


(a) 0.6 µm and 3.6 µm.

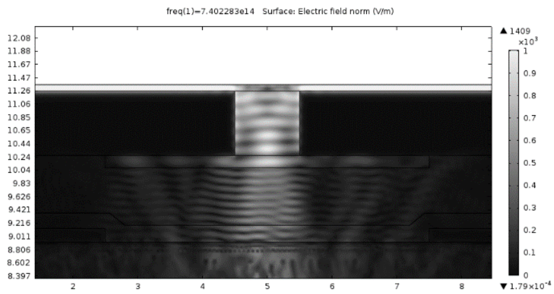


(b) 0.6 µm and 4.6 µm.

Fig. 9: Electric field profiles in structure for designed finger length and distance between ohmic contacts as depicted.



(a) 1 µm and 4 µm.



(b) 1 µm and 5 µm.

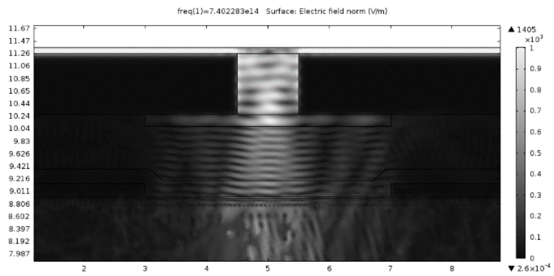
Fig. 10: Electric field distribution in structure for designed finger length and distance between ohmic contacts as depicted.

gated sample as well as for structure for designed finger length and distance between ohmic contacts 1 µm and 4 µm in Fig. 10(a) and 1 µm and 5 µm in Fig. 10(b).

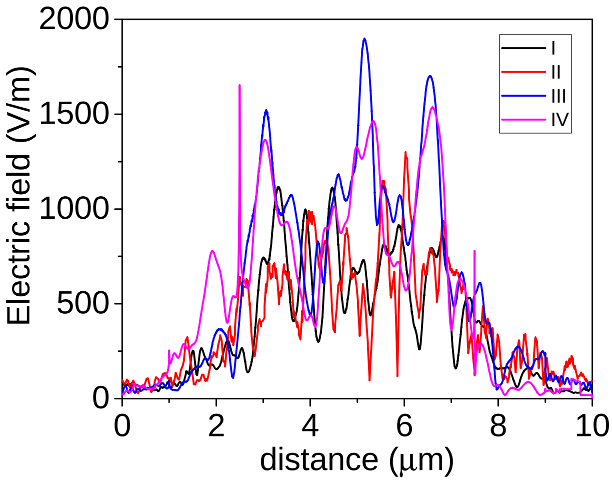
Optical effects occurring during exposure were also remarkable for the samples of designed finger length and distance between ohmic contacts as 5 µm and 8 µm and 5 µm and 9 µm (not shown) presented in Fig. 11(a) and Fig. 11(b).

The desired electric field distribution and profiles in photoresist are presented in Fig. 12. From the simulation structure the Y-gap was excluded. Compared to previously shown electric field distributions that in Fig. 12 has regular shape what permitted to obtain designed finger length. The phenomena indicate great influence of Y-gap on resulting gate lengths.

The simulation results shown the significant influence of Y-gap on the electric field distribution in the photoresist. The smallest value of relative error was

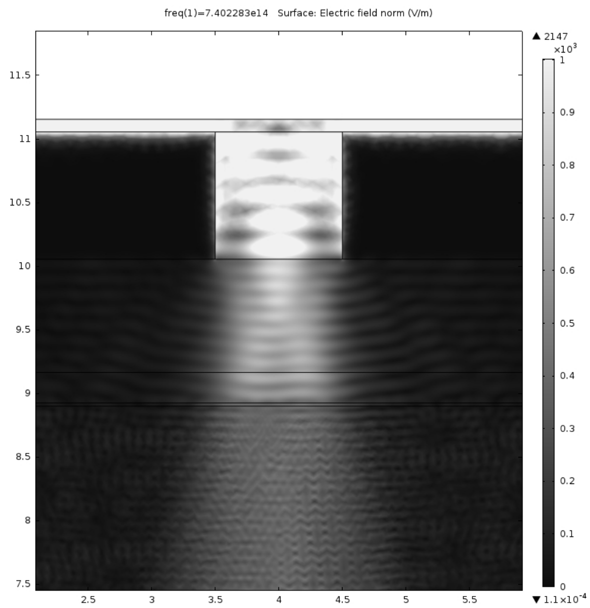


(a) Electric field distribution.

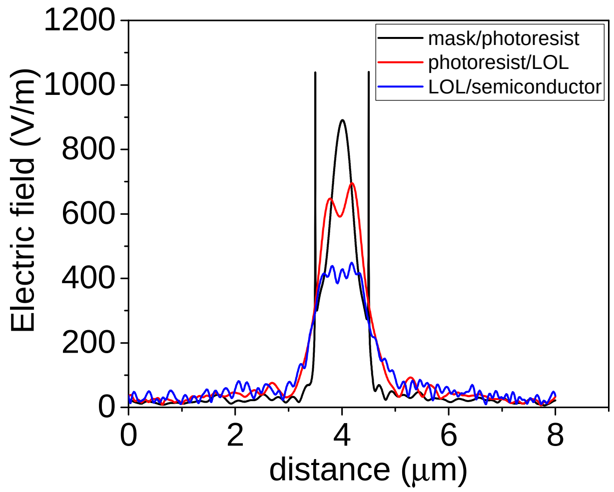


(b) Electric field profiles.

Fig. 11: Electric field distribution and profiles in structure for designed finger length and distance between ohmic contacts of 5 µm and 8 µm.



(a) Electric field distribution.



(b) Electric field profiles.

Fig. 12: Electric field distribution and profiles in structure for designed finger length of 1 µm without Y-gap.

observed for finger parts placed between ohmic paths on top of mesas. Apart from thicker lift-off double layer between ohmic paths the phenomenon could be a result of occurrence of the smallest Y-gap compared to that for test fingers placed on mesa and outside of it. The effect of separation distance was studied already in [8]. Results of simulation did not give an explanation of larger values of relative error for smaller distance between ohmic paths.

4. Conclusions

In the paper, the technological factors influencing test structure gate length were described. The standard deviation of fingers length was the smallest for fingers parts located between the ohmic contacts paths. Also the smallest value of relative error was obtained for finger parts placed between ohmic paths on top of mesas independently for both values of distance between ohmic contact paths. The relative error of test structures fingers lengths indicated affection of ohmic contact paths distance on the lengths. Larger values of relative error were observed for smaller distance between ohmic contacts.

The simulation results reveal great impact of Y-gap presence under the mask on the electric field distribution in the photoresist. The smallest value of relative error for finger parts placed between ohmic paths on top of mesas could be a result of occurrence of the smallest Y-gap compared to that for test fingers placed on and outside of mesa. Results of simulation did not bring any explanation of larger values of relative error for smaller distance between ohmic paths.

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