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***Abstract*—A new AlGaN/GaN heterostructure is proposed to achieve a normally-off behavior for GaN HEMTs. It relies on multiple P-GaN wells epitaxial regrowth along the gate. Simulation results are presented by focusing on the physical and geometrical parameters of the P-GaN wells. The normally-off behavior of the novel HEMT is demonstrated.**

***Keywords*—HEMT; P-GaN gate; normally-off; TCAD simulations**

I. INTRODUCTION

AlGaN/GaN high-electron mobility transistors (HEMTs) have attracted worldwide attention in power electronics as candidates for next-generation of high-speed switching devices. Thanks to the large electric field of GaN and the high carrier mobility and density in the two-dimensional electron gas (2DEG), AlGaN/GaN HEMTs can achieve high breakdown voltage and realize ultrahigh power density operation with low power losses.

While most of the demonstrated AlGaN/GaN HEMTs are inherently normally-on with a negative gate threshold voltage, normally-off mode is strongly demanded to fulfill the requirements of power electronics applications; indeed normally-off devices are inherently secure and suitable for energy converters requiring specifically high system reliability. Several approaches, each with its own limitations, have been proposed to convert the inherent depletion mode (normally-on) into an enhancement one (normally-off). The recess of the AlGaN barrier under the gate (or recessed gate) [1,2], Fluorine plasma ion implantation [3], oxygen treatment [4], gate injection transistor (GIT) [5] and P-GaN gate [6,7] are the most developed ones.

In this paper, we propose a new HEMT structure that combines two of these approaches i.e. recessed and P-GaN regrowth gate. The use of a P-GaN layer on the AlGaN/GaN heterostructure under the gate contact lifts up the conduction band level, inducing the depletion of the two dimensional electron gas (2DEG) channel, even in the absence of an external bias, thus ensuring the normally-off behavior.

The novelty of our structure relies on the gate conception: it is characterized by the implementation of a succession of P-GaN wells spaced by active AlGaN/GaN zones along the gate as shown on Fig.1. A lateral depletion effect takes place, allowing the decrease in the 2DEG density on each well sidewall. By acting on the well topology, the 2DEG channel can be fully depleted or not.

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Design and optimization of P-GaN wells are described with a focus on the influence of their geometrical parameters (width, depth and spacing) and on the influence of the technological parameters of both the AlGaN layer (thickness and aluminum content) and the GaN wells (P doping concentration). The simulated electrical transfer characteristics of the novel AlGaN/GaN HEMT are presented, highlighting the normally-off behavior. In the last section, we report on the technological developments performed for fabricating the nanostuctured P-GaN gate HEMT.

II. DEVICE STRUCTURE

A. HEMT description

Fig.1 shows different schematic views of the new AlGaN/GaN HEMT with multiple P-GaN wells along the gate. Fig. 1a is a 3D view of the whole HEMT. Fig. 1b is a schematic cross section along the gate showing the alternation of P-GaN wells and AlGaN/GaN active zones. The schematic cross section along the drain-source axis is drawn across a P-GaN well (Fig. 1c) and between two wells (Fig. 1d).

The epitaxial layers parameters used for the simulations are the following: a 20 nm $Al_{0.2}Ga_{0.8}N$ barrier, a 1.7 µm GaN layer, a resistive AlGaN buffer layer, a 200 nm AlN transition layer on a silicon substrate. The GaN and AlGaN are considered to be non intentionally doped (NID) at 1 x 10^{16} cm^{-3} and 1 x 10^{15} cm^{-3} respectively. The gate-source spacing, the gate-drain spacing and the gate length are 1 µm, 5 µm and 300 nm respectively. The source and drain contacts are Schottky ones.

B. Simulated elementary cell description

2D and 3D simulations were performed with SENTAURUS TCAD software. In order to first evaluate the impact of the insertion of P-GaN wells through the layers stacking, we present simulations at the thermodynamic equilibrium. The studied structure being symmetrical and in order to minimize calculation times, we considered only a half cell as described on Fig. 2.

As mentioned in the introduction, the insertion of P-GaN wells along the gate leads to the formation of PN junctions formed by the P-regions and the AlGaN and GaN active regions neighboring the different well sides: a space charge region (SCR) or depleted zone is naturally created, which extension depends on the wells design. The on-state or off-state behavior of the HEMT is the consequence of the SCR modulation obtained by applying an electrical potential on the P-GaN

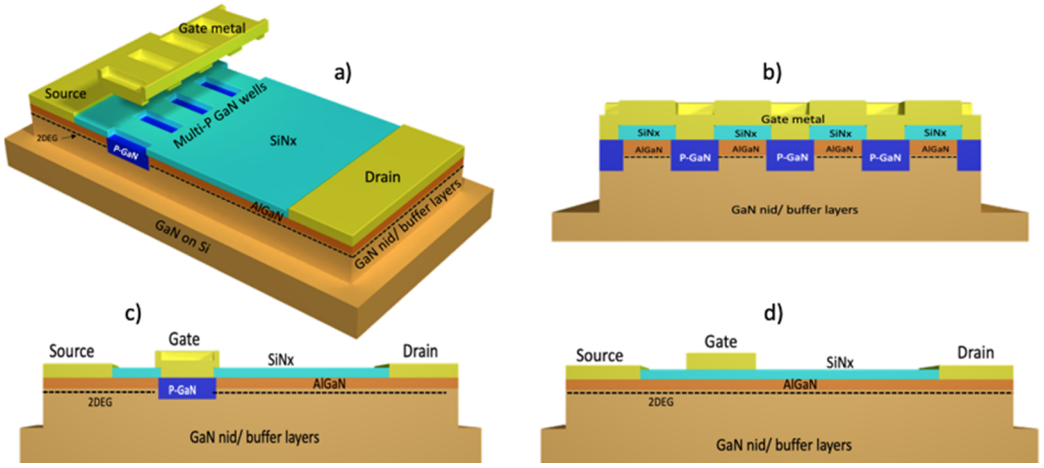

Fig. 1. 3D and cross sectional views of the multi P-GaN wells gate HEMT

regions, i.e. on the gate contact. The major parameters which directly influe on the lateral SCR extension are the following: e_T, L_T and Na respectively the depth, width and doping of the P-GaN wells and D_T the spacing between two wells. We also condidered the influence of the Al content of the AlGaN barrier layer.

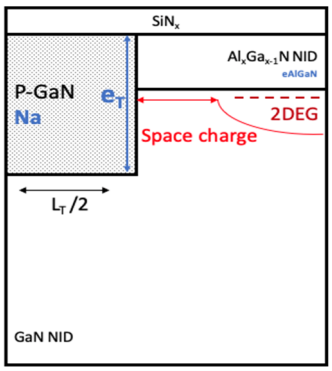

Fig. 2. Schematic cross sectional view of the simulated half cell

III. Simulation Results and Discussions

A. *Influence of the P-GaN depth e_T*

2D simulations have been first performed to evaluate the influence of the well depth on the lateral space charge extension between the P-GaN region and the 2DEG as illustrated on Fig. 3. The P-GaN width L_T is fixed to 100 nm, the AlGaN layer width to 20 nm, and we varied the doping concentration (Na) of the P-GaN region for two values of the aluminum content of the AlGaN layer, $x_{Al} = 0.25$ and $x_{Al} = 0.15$.

The results are reported on Fig. 4: the channel depletion width increases with e_T until achieving a maximum value for e_T around 100 nm. This depth value will be retained for the following simulations. The depletion width through the channel also increases with Na, and decreases when the aluminum content increases. For example, for a P doping concentration varying from 1 x 10^{18} cm^{-3} to 1 x 10^{19} cm^{-3} and x_{Al} fixed to 15%, the depletion width extends from 30 nm to 45 nm respectively.

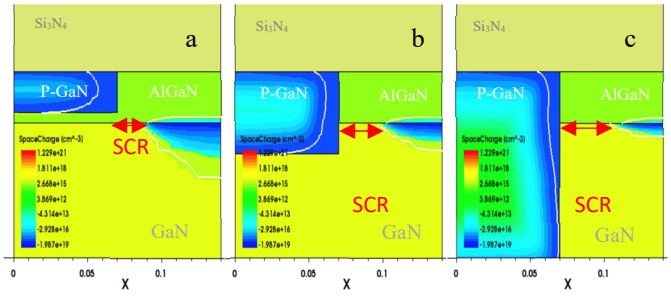

Fig. 3. Example of 2D simulations of the space charge region extension for different P-GaN well depths: a) $e_T = 20$ nm, b) $e_T = 35$ nm, c) $e_T = 100$ nm

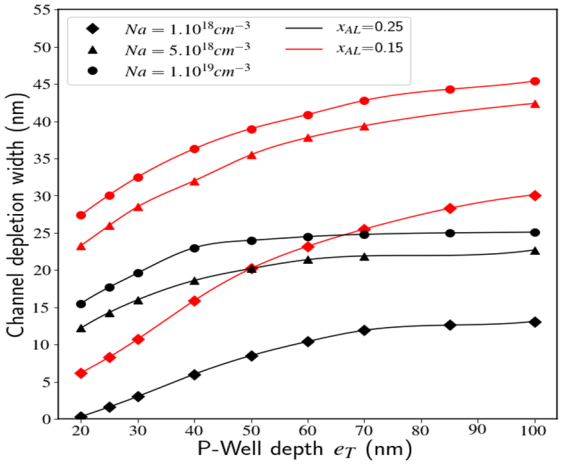

Fig. 4. Simulated channel depletion width variations as a function of the P-GaN well depth, for two aluminum contents (0.25 and 0.15) and different P-GaN doping concentrations (1 x 10^{18} cm^{-3}, 2 x 10^{18} cm^{-3} and 1 x 10^{19} cm^{-3})

B. *Influence of the aluminum content x_{Al}*

We plotted on Fig. 5 the variations of the lateral depletion width as a function of the polarization charges density at the interface AlGaN/GaN. Indeed, the 2DEG channel is the result of the piezoelectric and spontaneous polarization charges through these two layers: the higher the aluminum content, the higher the charges density and, as a consequence, the higher the 2DEG

density. To obtain the normally-off functionality for this HEMT, it will be necessary to maximise the lateral depletion width. For an Al content of 20 %, value commonly used, and a P-doping concnetration of 1 x 10^{19} cm^{-3} e.g., the optimum value of the lateral space charge extension through the 2DEG is 28 nm.

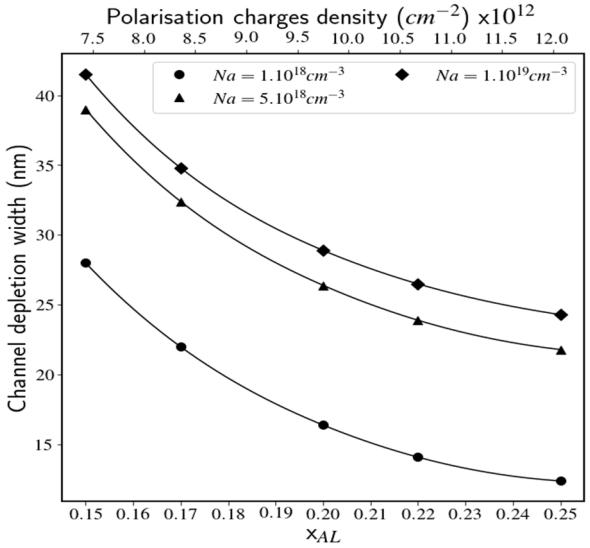

Fig. 5. Simulated variations of the channel depletion width as a function of the aluminum content x_Al and the polarisation charges density for different P-doping concentrations

C. *Influence of the P-GaN well width L_T*

We have also analyzed the impact of the well width L_T on the width of the depleted zone which extends on each side of the P-GaN regions. The behavior can be fitted by an exponential function from which we can extract the minimum value L_{Tmin} of the well width at 95 % of the maximum SCR extension width. In Fig. 6a, it can be seen that the space charge no longer extends from a well width value corresponding to L_{Tmin}.

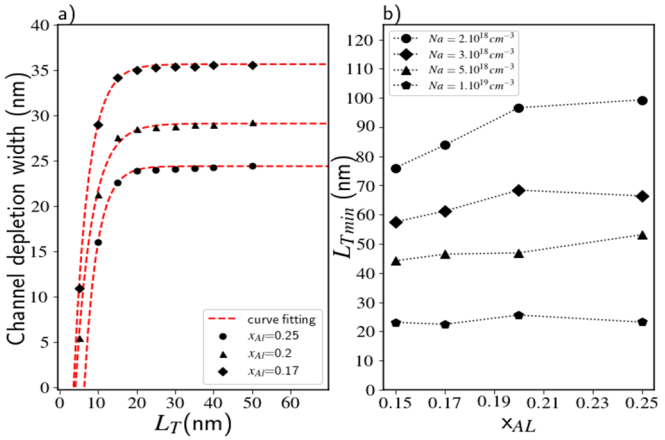

Fig. 6. a) Simulated variations of SCR width as a function of L_T for a 1x$10^{19}$$cm^{-3}$ P-GaN doping concentration and different aluminum contents x_{Al}; b) L_{Tmin} variations as a function of x_{Al} for different P-doping concentrations (e_T = 100 nm)

For a 1 x 10^{19} cm^{-3} P-GaN doping concentration, the minimum value is 25 nm whatever the aluminum content. We have determined the L_{Tmin} value necessary to achieve a maximum SCR extension, for various P-GaN doping concentrations and Al contents, with a 100 nm well depth (Fig. 6b). For P-doping concentrations higher than 5 x 10^{18} cm^{-3}, there is a little influence of x_{Al}. For lower doping concentrations, it will be necessary to increase L_T in order to obtain an optimum depletion width.

D. *Influence of the well spacing D_T*

The geometrical and physical parameters of the P-GaN wells have been optimized to obtain a maximum depletion extension for each one. We consider now a whole cell, comprising two wells spaced by the length D_T. We have determined the spacing necessary to achieve the SCRs overlapping, thus inducing a full channel depletion and obtaining the HEMT's self-blocking.

It is well known that it is necessary to lift the conduction band energy level E_C above the Fermi level to achieve the normally-off functionality for the HEMT by depleting the channel at the AlGaN/GaN interface. So we have analyzed the evolution of the minimum E_C value extracted at the middle of the channel as a function of two well spacing for different Na doping concentration values (Fig. 7). The minimum energy decreases linearly when D_T increases to reach a threshold when the channel is no more depleted, so rending the HEMT normally-on. This spacing threshold increases with the P-GaN doping concentration.

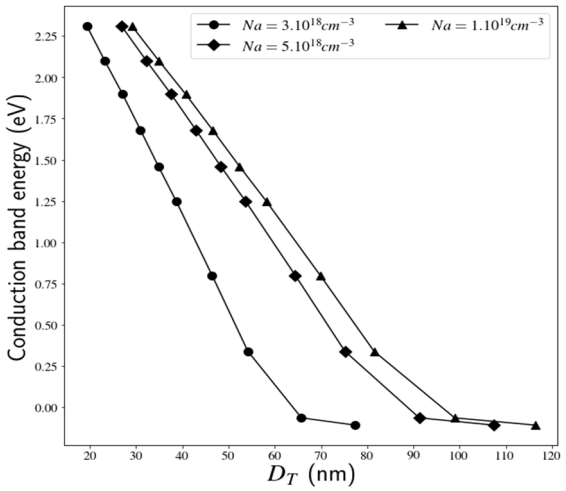

Fig. 7. Simulated variations of the conduction band energy level versus the well spacing D_T for different P-GaN doping concentrations

Considering the conventional P-GaN normally-off HEMTs studied in the literature, the only way to modify the threshold voltage V_{TH} is acting on the P-GaN doping concentration. The novel HEMT structure presented in this paper offers a better flexibility with the advantage to modulate V_{TH} by varying either the P-GaN wells geometrical parameters or their spacing or their doping concentration.

E. *On-state behavior of the multi P-GaN well gate HEMT*

3D simulations have been performed to observe the on-state behavior of our HEMT structure. The electron mobility in the channel is fixed at 2000 cm^2/V.s taking into account the models

of the mobility degradation of the electrons saturation speed at strong electric field. We also considered a Schottky contact on the P-GaN wells. Due to the symmetry of the structure, a half cell is still studied.

The maximum drain saturation current I_{Dmax} and the threshold voltage V_{TH} are extracted from the simulated transfer characteristics I_D (V_{GS}) plotted for different channel widths D_T and a drain voltage V_{DS} of 1 V (Fig. 8). The well parameters are the optimum ones defined on the previous simulations, i.e. L_T = 30 nm, e_T = 100 nm, x_{Al} = 0.20 and Na = 10^{19} cm^{-3}. The normally-off behavior of the new HEMT structure is validated with positive threshold voltages. When the channel width increases, V_{TH} decreases as it was expected from previous 2D simulations.

With our structure, we can achieve V_{TH} values higher than those obtained for standard P-GaN HEMTs [8] and FiNFET AlGaN/GaN HEMT topologies regarding the same channel width [9,10]. However, we can see that the maximum current value strongly depends on the channel width, due to the area aspect ratio between the P-GaN and the 2DEG channel regions. The maximum drain current value is around 1 kA.cm^{-2} which is a coherent value similar than the ones found in literature [11].

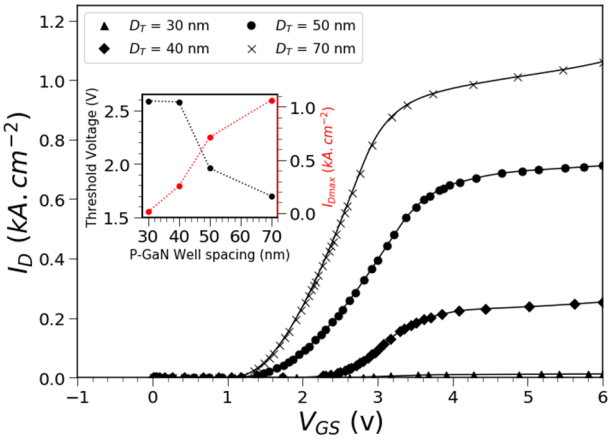

Fig. 8. Simulated transfer characteristics I_D (V_{GS}) at V_{DS} = 1 V for various D_T with L_T = 30 nm, e_T = 100 nm, x_{Al} = 0.20, Na =1 x 10^{19} cm^{-3}, and a Schottky contact on the gate.

IV. Technological Developments

Most of the P-GaN gate HEMT technologies developed are based on the selective GaN layer etching on top of the AlGaN barrier to define the source and drain access regions. However, the plasma-induced damages may affect the electrical performances of the device due to surface leakage currents. One technology that overcomes these problems and that we have developed in our laboratory consists in fabricating the Mg-doped P-GaN region by selective epitaxy using a SiO_2 growth mask [12,13].

We present in this part the results obtained for a normally-off HEMT that we have fabricated by associating both recess-gate and P-GaN regrowth technics [14-16] with the GaN layer regrown on the whole gate area. The validation of this process led us to develop afterwards the new normally-off HEMT structure presented in this paper with multi P-GaN wells along the gate.

A. Normally-off HEMT with a MBE regrown P-GaN gate

The HEMT structure was characterized by an AlGaN barrier of 25 nm thick with an aluminum rate of 20 %. At first, a 100 nm thick silicon oxide SiO_2 layer was deposited by PECVD (Plasma Enhanced Vapor Deposition), acting as a mask for both the AlGaN gate etch and the selectively GaN regrowth. After a CF_4 RIE etch of the SiO_2 layer to define the gate region, a Cl_2 partial etching of the AlGaN layer was performed by ICPECVD with the following conditions: RF power of 60 W, pressure of 5 mTorr and Cl_2 flow rate of 10 sccm. For an etch time of 35 s, 19 nm of AlGaN was removed. A 50 nm GaN layer P-doped with Magnesium (Mg) was then regrown in a MBE (Molecular Beam Epitaxy) reactor with a nominal acceptor concentration of Na-Nd of 4 x 10^{18} cm^{-3}.

Figure 9 shows a TEM cross-section view of the gate region with the regrown P-GaN layer on the etched AlGaN layer. The analysis highlights the perfect nucleation of the GaN layer on the etched AlGaN layer. The next technological steps concerned the mesa isolation and the gate, source and drain metallisations.

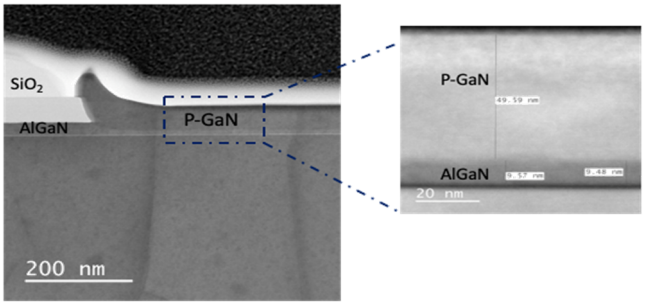

Fig. 9. TEM cross-section view of 50 nm P-GaN layer regrown by MBE on the etched AlGaN layer.

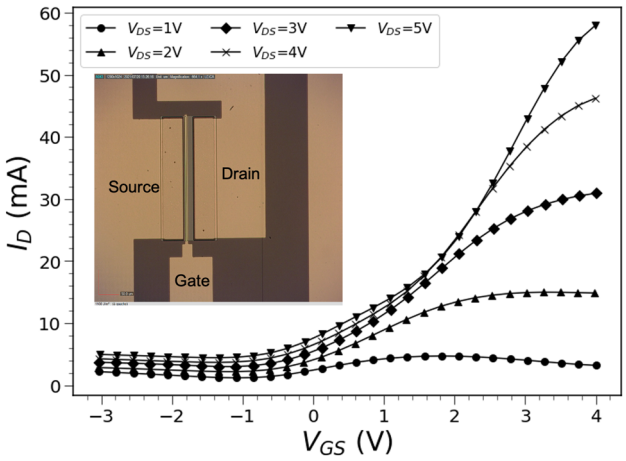

Fig. 10. View of the recessed and regrown P-GaN gate normally-off HEMT developed at LAAS and measured transfer characteristics I_D (V_{GS}) for various V_{DS}, with Na = 4 x 10^{18} cm^{-3} and a Schottky contact on the P-GaN.

The measured transfer characteristics I_D (V_{GS}) of the fabricated HEMT for various V_{DS} values are reported on Fig. 10, for a Schottky contact on the gate. The normally-off behavior was demonstrated with positive threshold voltages around 1 V.

B. *Normally-off HEMT with a multi P-GaN wells gate*

The fabrication of the novel proposed HEMT structure is in progress. The first technological step we have developed is the e-beam lithography of the 200 nm thick HSQ resist at the nanometric scale in order to define the 50 nm wide active regions separating the different P-GaN regions. Fig.11 shows a MEB view after the lithography of the HSQ lines across the gate, which is delimitated by the SiO_2 layer, and the BCl_3 etching of the AlGaN/GaN layers with both HSQ and SiO_2 as an etch mask, thus resulting in the formation of the different wells. The next step of the process will be the selective area growth of the P-GaN regions inside the etched wells.

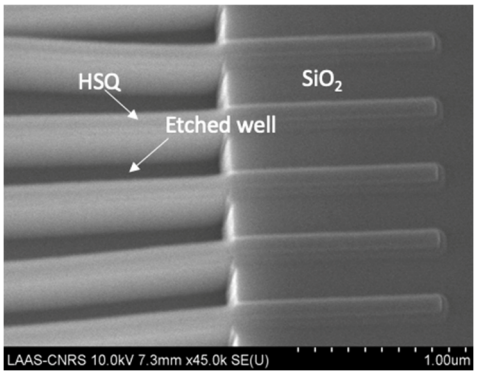

Fig. 11. MEB view of the multiwells along the gate after HSQ e-beam lithography and AlGaN/GaN BCl_3 etching.

V. CONCLUSION

A new normally-off AlGaN/GaN HEMT structure with multiple P-GaN wells along the gate is proposed in this paper. The P-GaN HEMTs developed up to now necessitate an accurate control of the gate recess with the disadvantage of channel mobility degradation. In our structure, the 2DEG channel properties are maintained between two wells. A lateral space charge region extends on each side of them, thus depleting the adjacent channel created by the AlGaN/GaN heterostructure.

2D simulations have highlighted that with an appropriate design of the well i.e. depth, width, spacing between each one, and P-GaN doping concentration, we can obtain the normally-off functionality with a degre of freedom in the choice of the AlGaN layer parameters (thickness and aluminum content).The benefit of the proposed HEMT was demonstrated from 3D simulations, positive threshold voltages being achieved. This structure paves the way for the integration of advanced power functions.

The HEMT fabrication is in progress: the critical technological steps such the wells shaping at the nanometric scale and the GaN regions regrowth have been developed.

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