A Novel Analytical Model for Surface Electrical Field Distribution and Optimization of TFSOI RESURF Devices*

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Abstract: A novel analytical model for the thin film silicon on insulator (TFSOI) reduced surface field (RESURF) devices has been proposed. Based on the 2-D Poisson equation solution, the analytical expressions for the surface potential and field distributions are derived. From this analysis, the optimum design condition for the maximum breakdown voltage is obtained. The dependence of the maximum breakdown voltage on the drift region length is examined and the relationship between the critical doping concentration and the front- and back-interface oxide layer thickness is discussed. The numerical simulation performed by the advanced semiconductor simulation tool, DESSIS-ISE, has been shown to support the analytical results.

Key words: TFSOI RESURF devices; surface electric field distribution; potential profile; breakdown voltage; optimum design

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1 Introduction

Silicon-on-insulator (SOI) technology offers considerable advantages in the implementation of low voltage CMOS signal processing circuits in conjunction with high voltage MOS drives on the same chip[1—3]. A key issue in the development of SOI HVIC (high voltage integrated circuits) is the design and realization of a RESURF structure sustaining the high voltage. Thus, the surface electric field distribution that determines the breakdown voltage of the SOI RESURF structure is of significant importance. Many previous works have been focused on the numerical analysis or experiments of TFSOI RESURF devices[3—5]. Some analytical models have been presented based on the especial assumptions such as a parabolic curve profit[6—7] or a cylindrical solution[8]. However, these assumptions need further proving and the optimum design of the RESURF structure should be gone into. In fact, it has little effect on the closed-form analytical solution at the maximum breakdown voltage, so it is necessary to discuss such a structure and model the effect of the interface oxide layers on the critical doping concentration.

In this paper, based on the 2D solution of the Poisson equation solution, a novel analytical model for the surface potential and field distributions of TFSOI RESURF devices is proposed. The theoretic results indicate that peak electric fields appear at the junction edges, where the relative magnitude strongly depends on the doping and thickness of a silicon film as well as the thickness of the front and

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back interface oxide layers. The ideal field distribution equals the two peak-fields presenting at the p$^+$ n$^-$ and n$^+$ n$^-$ junction edge, which can determine the critical doping concentration in the drift region at breakdown. The critical doping concentration in the drift region at the maximum breakdown voltage is directly related to the thickness of front- and back- interface oxide layer as well as that of the silicon film. Thus, an ideal field profile is obtained to reach the maximum breakdown voltage via optimizing the device structure parameters. The increase in the maximum breakdown voltage along with the length of the drift region shows a saturation tendency after numerical analysis. All analytical results have been verified by the advanced semiconductor simulation tool, DESSIS-ISE[9].

2 Analytical Model

A schematic cross section of the TFSOI RESURF device's structure with a doping concentration N_d is shown in Fig. 1, where t_{Si} is the thickness of the silicon film with the dielectric constant ϵ_s; t_b and t_f are the thickness of the buried oxide layer and the field oxide one with the dielectric constant ϵ_{ox}.; x and y are the horizontal and vertical positions from the p diffusion edge relative to the silicon surface, respectively. The drift region length of the device is defined as L, which is under the field oxide layer. The device is biased in the off-state configuration. The substrate, source and gate are grounded while the drain is biased to a positive voltage V_b.

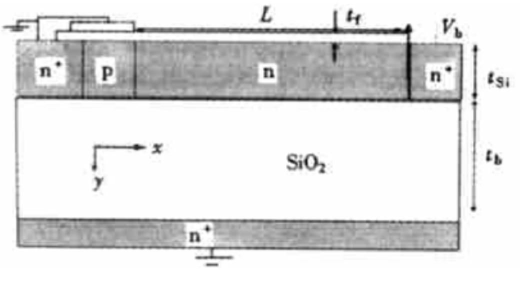

FIG. 1 Cross-Section of TFSOI RESURF Device

The potential function $\phi(x, y)$ in the silicon film must satisfy the Poisson equation, so:

$$\frac{d^2\phi(x,y)}{dx^2}+\frac{d^2\phi(x,y)}{dy^2}=-\frac{qN_d}{\epsilon_{Si}} \qquad (1)$$

As shown in Fig. 1, the region in this investigation is a box drift one. It is possible to derive a 1-D equation from the 2-D Poisson equation to describe the surface potential in the lateral coordinate (x). In this work, a general analysis based on the theory of Reference[10] integrates the Poisson equation over the y-direction

$$\int_0^{t_{Si}}\frac{\partial^2\phi(x,y)}{\partial x^2}dy+E_y(x,0)-E_y(x,t_{Si})=-\frac{qN_d}{\epsilon_{Si}}t_{Si} \qquad (2)$$

Assuming a 1-D electrical field in the SiO_2 material, the continuity of the electric flux along the front- and back- Si/SiO_2 interface makes the boundary conditions of (2) satisfy

$$E_y(x,0)=-\frac{\epsilon_{ox}}{\epsilon_{Si}}\times\frac{\phi_f(x)-V'_{gs}}{t_f} \qquad (3)$$

for the front Si/SiO_2 interface, while

$$E_y(x,t_{Si})=\frac{\epsilon_{ox}}{\epsilon_{Si}}\times\frac{\phi_b(x)-V'_{sub}}{t_b} \qquad (4)$$

for the back Si/SiO_2 interface, respectively. Where, $\phi_f(x)\equiv\phi(x,0)$ and $\phi_b(x)\equiv\phi(x,t_{Si})$ are the potential function along the front Si/SiO_2 interface and back interface; $V'_{gs}=V_{gs}-V_{FB,f}$ and $V'_{sub}=V_{sub}-V_{FB,b}$ are the effective gate-to-source and substrate bias voltage; $V_{FB,b}$ and $V_{FB,f}$ are the front- and back-channel flat-band voltage, respectively.

Because the gate and substrate biases are zero, neglecting the influence of the difference in work function between the metal and semiconductor on the electric field, the electric fields at the front- and back- interface can be expressed as

$$E_y(x,0)=-\frac{\epsilon_{ox}}{\epsilon_{Si}}\times\frac{\phi_f(x)}{t_f} \qquad (5)$$

$$E_y(x,t_{Si})=\frac{\epsilon_{ox}}{\epsilon_{Si}}\times\frac{\phi_b(x)}{t_b} \qquad (6)$$

From (2) to (6), it is obtained

$$\int_0^{t_{Si}}\frac{\partial^2\phi(x,y)}{\partial x^2}dy-\frac{\epsilon_{ox}}{\epsilon_{Si}}\times\frac{\phi_f(x)}{t_f}-\frac{\epsilon_{ox}}{\epsilon_{Si}}\times\frac{\phi_b(x)}{t_b}=-\frac{qN_d}{\epsilon_{Si}}t_{Si} \qquad (7)$$

According to the principle of TFSOI RESURF device, SOI layer should be completely depleted and the depletion approximation is suitable for the analytical model. At the first-order approximation, on the assumption that $\frac{\partial^2\phi_f(x,y)}{\partial x^2} \approx \frac{\partial^2\phi_f(x)}{\partial x^2}$, the relation between $\phi_f(x)$ and $\phi_b(x)$ is derived by solving the Poisson's equation (1) in vertical direction

$$\phi_b(x) = \phi_f(x) - E_y(x,0)t_{Si} - \frac{1}{2}\left[\frac{qN_d}{\epsilon_{Si}} + \frac{\partial^2\phi_f}{\partial x^2}\right]t_{Si}^2 \tag{8}$$

By putting everything into (2) and making further simplification, (2) then transforms into a 1-D differential equation:

$$\frac{d^2\phi_f(x)}{dx^2} - \alpha_f\phi_f(x) = \beta_f \tag{9}$$

with $\alpha_f = \frac{t_f + t_b + \frac{\epsilon_{ox}}{\epsilon_{Si}}t_{Si}}{t_f t_{Si}\left[\frac{t_{Si}}{2} + \frac{\epsilon_{Si}t_b}{\epsilon_{ox}}\right]}$ and $\beta_f = -\frac{qN_d}{\epsilon_{Si}}$

Solve (9) with the boundary conditions that $\phi_f(0) = 0$ and $\phi_f(L) = V_b$ and define that $\partial_f = -\frac{\beta_f}{\alpha_f}$ and $\tau_f \equiv (1/\alpha_f)^{1/2}$, we will get:

$$\phi_f(x) = \partial_f + \frac{(V_b - \partial_f)\sinh\left[\frac{x}{\tau_f}\right] - \partial_f\sinh\left[\frac{L-x}{\tau_f}\right]}{\sinh\left[\frac{L}{\tau_f}\right]} \tag{10}$$

The surface field profile along the semiconductor surface is obtained by differentiating (10)

$$E(x,0) = -\frac{d\phi_f}{dx} = -\frac{(V_b - \partial_f)\cosh\left[\frac{x}{\tau_f}\right] + \partial_f\cosh\left[\frac{L-x}{\tau_f}\right]}{\tau_f\sinh\left[\frac{L}{\tau_f}\right]} \tag{11}$$

3 Results and Discussion

Based on the above analytical expressions, the potential and electric filed distributions along the semiconductor surface can be readily demonstrated, and the effect of the front- and back- interface oxide layers and silicon film on the potential and field can also be analyzed. In order to verify the proposed model, 2-D device simulation is performed by using DESSIS-ISE for the same structure. In the following discussion, the curves denote the analytical results while the black points do the numerical results.

Figure 2 shows the common TFSOI RESURF device's potential and field profiles in the lateral direction with different silicon film doping concentration N_d. All defaulting parameters are shown in the figures.

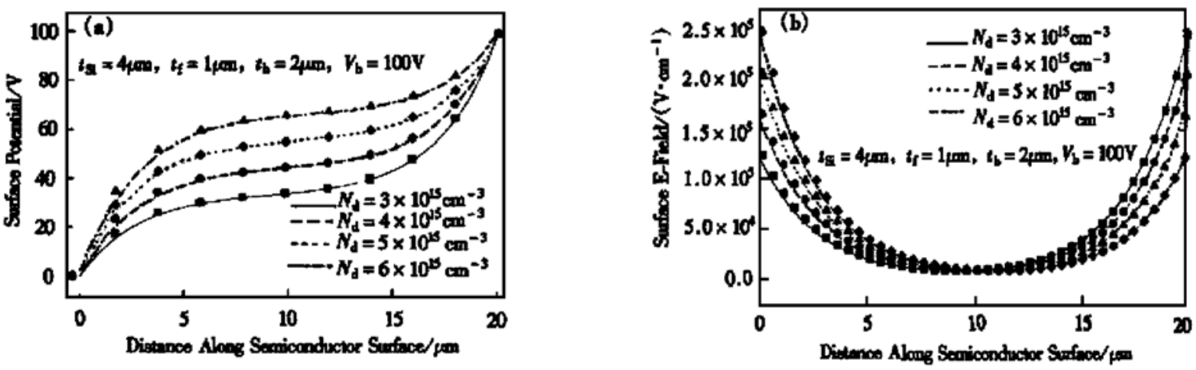

FIG. 2 Surface Potential (a) and Field Distributions (b) Along Semiconductor Surface with Different Silicon Film Doping N_d

Figure 2(a) indicates that the potential profile along the silicon surface is similar to the form of an abrupt junction at the edges of p^+n^- junction and n^+n^- junction where the depletion region exists. The total potential profile difference at both the junction edges coincides with the applied reverse voltage. From Fig. 2, one can see that with the increase of the doping concentration, the potential difference at the p^+n^- junction increases, while that at the n^+n^- junction reduces. The potential difference at the n^+n^- junction is expected to decrease further to zero at the maximum doping value, where the depletion region can not punch through to the n^+n^- junction.

Figure 2 (b) shows the surface field profile along the silicon film surface with different silicon film doping. It is evident that there are two edge field peaks along the silicon surface at the p^+n^- and n^+n^- junctions, one at the former edge and the other at the latter one, which coincides with the numerical analytical results[4—5]. From Fig. 2 (b), it is found that the relative magnitude of the two edge field peaks strongly depends on the silicon film doping. With the increase of the doping concentration, the peak field of the p^+n^- junction increases but that of the n^+n^- junction decreases, i.e., the highest electric field peak value moves from the interface of n^+n^- junction to that of p^+n^- junction with the increase of doping concentration, as is responsible for the variation in the potential profile. As a result, the breakdown point moves from the n^+n^- junction edge to the p^+n^- one on the silicon surface as the doping concentration of the n^- drift region increases beyond the critical value, at which two peak electrical fields at the junction edges are equal and the maximum breakdown voltage appears. The objective of the optimum design of SOI RESURF power devices is to find the critical doping concentration, which has been proved by the numerical simulation decreasing with the thickening of the buried oxid[7]. Based on above analytical expressions, we have obtained sufficient details to predict the critical concentration and its relation with other structure parameters, such as the silicon film and oxide layer thickness in the following discussion.

From Fig. 2, the analytical result and the numerical analysis is found in good agreement with each other in the most of the drift region except for the smaller discrepancies around the both junction edges that are due to the effects of the junction curvature and the edge field plate of the gate and drain electrode. In following discussions, we can still encounter this kind of accordance and discrepancies.

Figure 3 demonstrates the potential and field profiles along the semiconductor surface with different thickness of the field oxide layer.

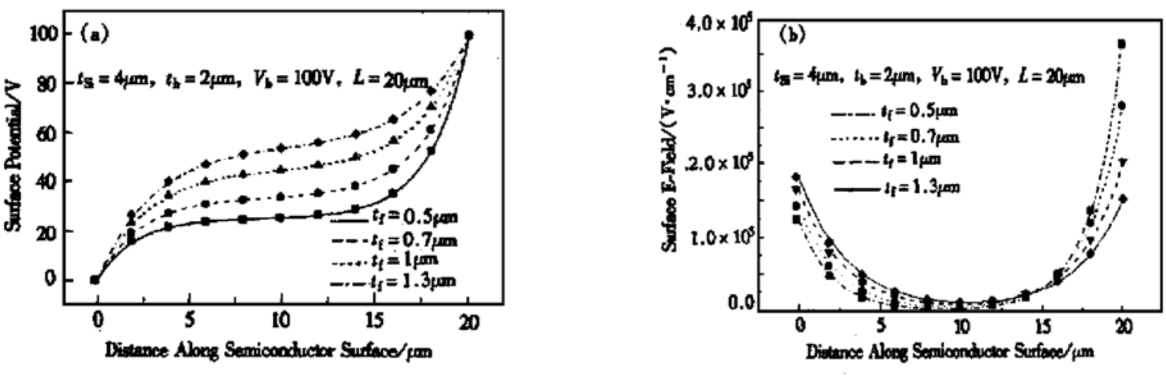

FIG. 3 Surface Potential (a) and Electrical Field (b) Distributions in Lateral Direction with Different Field Oxide Thickness

It is very interesting that the effect of the field oxide thickness on potential and field profiles is similar to that on silicon film doping concentration. With the increase of t_f, the maximum potential difference shifts from the n^+n^- junction to p^+n^- junction, while the maximum peak field point is transformed from the former to the latter. Because the maximum field often appears at the p^+n^- junction when the avalanche breakdown occurs, the field oxide thickness will weaken the breakdown voltage of TFSOI RESURF devices as shown in Reference[7].

Figure 4 demonstrates the potential and field profiles along the semiconductor surface with different buried oxide layer thickness.

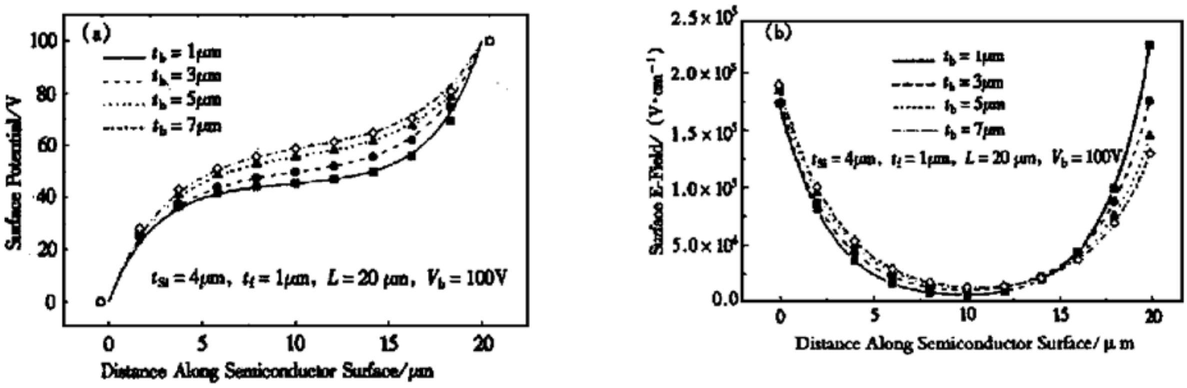

FIG. 4 Surface Potential Profile (a) and Surface Electrical Field Distribution (b) in Lateral Direction with Different Buried Oxide Layer Thickness

In contrast, the buried oxide layer makes the potential difference at the p^+n^- junction decrease but increase at the n^+n^- junction. Corresponding with the change in the potential, the magnitude of the edge peak field reduces at the p^+n^- junction and increases at the n^+n^- junction with the buried oxide layer increasing. Due to the effect of the buried oxide layer, the RESURF devices can form a punch-through junction easily if the length of the drift region is small enough.

Please note that the effect of the field and buried oxide layers on the potential and surface field can compensate each other; one makes an edge peak field be reinforced, while the other makes it decrease. As a result, an ideal field profile, at which two edge peak electrical fields are equal, is obtained to calculate the maximum breakdown voltage in Reference[6] and later discussions.

4 Optimization

In the design of TFSOI RESURF devices, silicon film thickness, doping concentration, drift region length and the field and buried oxide layers are important parameters, which determine the characteristics of the devices. In the following discussion, we give some optimum relationships.

The expression of the surface electrical field given by (11) is of great interest because of the surface breakdown due to the field enhancement at the n^+n^- and n^-p^+ edges. The surface field expression along the lateral direction can be transformed into the following form

$$E(x) = \frac{\alpha}{\tau\sinh\left(\frac{L}{\tau}\right)}\left[S\cosh\left(\frac{x}{\tau}\right) + \cosh\left(\frac{L-x}{\tau}\right)\right] \quad (12)$$

where a dimensionless parameter $S = \frac{V_b}{\alpha} - 1$ represents the symmetrical characteristics of the surface field distribution. Obviously, when $S = 1$, the doping concentration in the drift region reaches the critical value, and the ideal electrical field profile at the breakdown voltage reaches its maximum value. So,

$$V_{b(max)} = 2\alpha \quad (13)$$

Therefore, the condition that $S = 1$ represents whether the device parameters can satisfy the optimum design condition. In an ideal case, the maximum edge field at the edges is

$$E_{max}(0) = E_{max}(L) = \frac{\partial\left[1 + \cosh\left(\frac{L}{\tau_f}\right)\right]}{\tau_f \sinh\left(\frac{L}{\tau_f}\right)} \quad (14)$$

As a result, the lateral breakdown voltage V_b due to the surface electrical field can be calculated form the avalanche breakdown condition of the critical electrical concept: $E_{max}(x) = E_c = 2.5 \times 10^5$V/cm, as is given as:

$$V_b = 2\partial = 5 \times 10^5 \tau_f \frac{\sinh\left(\frac{L}{\tau_f}\right)}{\left[1 + \cosh\left(\frac{L}{\tau_f}\right)\right]} \quad (15)$$

Figure 5 shows the comparison between the analytical and experimental maximum breakdown voltage versus the normalized distance parameter L/τ_f, which are in good agreement.

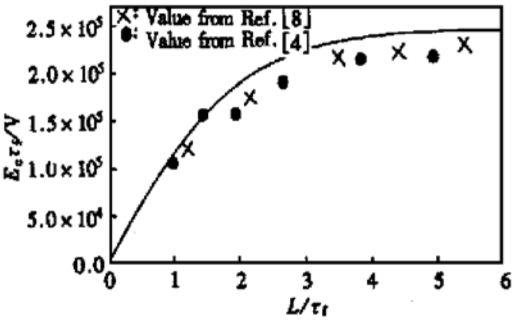

FIG. 5 Maximum Breakdown Voltage Versus Normalized Drift Region Length

In general, the longer the drift region length is, the higher the breakdown voltage will be. However, the maximum breakdown voltage nearly keeps constant once $L \geqslant 6\tau_f$, so the optimum design condition for the enough long drift region length $L \geqslant 6\tau_f$ becomes

$$\partial/\tau_f = E_c = 2.5 \times 10^5 \quad (16)$$

Thus, the relationship between the silicon film structure parameters, such as the critical doping concentration, the silicon film thickness and the interface oxide layer thickness for the optimum design, can be obtained and some useful conclusions are drawn.

Figure 6 shows the critical doping concentration decreases with the increase of the field oxide thickness, which is one of the requirements of RESURF. Meanwhile, the breakdown voltage continues to increase with the increase of the field oxide. However, due to limitation, the field oxide layer is always smaller than 4—5μm.

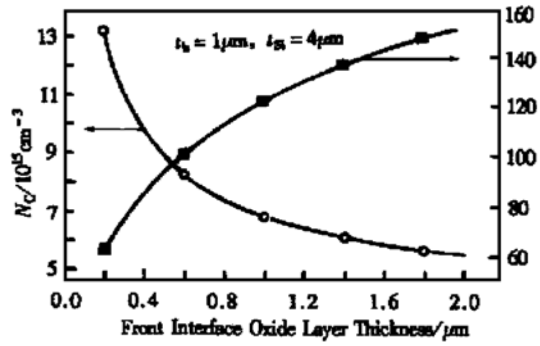

FIG. 6 Critical Doping Concentration and Breakdown Voltage Versus Field Oxide Layer Thickness

Figure 7 describes the influence of the buried oxide layer thickness on the critical doping concentration in the drift region. It is noted that the effect of the buried oxide layer on both the critical doping concentration in the drift region and the breakdown voltage is quite similar to that of the field layer

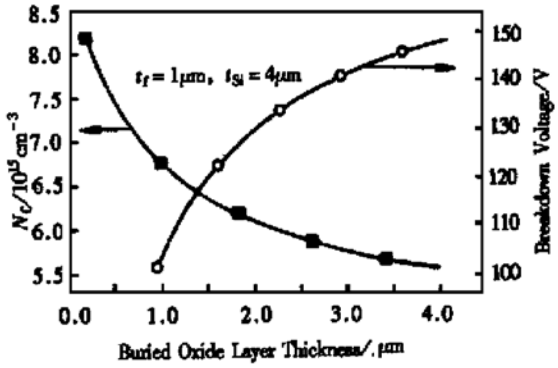

FIG. 7 Critical Doping Concentration and Breakdown Voltage Versus Buried Oxide Layer Thickness

thickness to them. Thus, there exist a trade-off between the oxide layer and critical doping concentration to meet the required breakdown voltage and accepted on-resistance of the TFSOI RESURF devices. In order to enhance the breakdown characteristics of the devices while maintaining the low on-resistance, an ideal surface field distribution is necessary and the critical doping concentration is of considerable importance. Therefore, the analytical model proposed here would be a powerful tool in the optimum design of TFSOI RESURF devices.

5 Conclusion

In this paper, the surface field distribution and the optimal parameter design of TFSOI RESURF devices have been studied. The dependence of the surface potential and electric field distributions on the drift region doping concentration and thickness as well as the influence of the field and buried oxide layer thickness have been analyzed. The optimum design condition has been examined, at which the ideal electrical field distribution is at the maximum breakdown voltage. The relationship between the critical doping concentration in the drift region and the field and buried oxide layer thickness has been discussed. All analytical results have been shown in agreement with those obtained by DESSIS-ISE simulation.

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TFSOI RESURF 功率器件表面电场分布和优化设计的新解析模型*

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摘要: 提出了 TFSOI RESURF 功率器件的表面电场分布和优化设计的新解析模型. 根据二维泊松方程的求解, 得到了表面电场和电势分布的相关解析表达式. 在此基础上, 推出了为获得最大击穿电压的优化条件。讨论了击穿电压和漂移区长度及临界掺杂浓度和场氧化层、埋氧化层的关系. 解析结果与半导体器件数值分析工具 DESSISE-ISE 得到的数值分析基本一致, 证明了新解析模型的适用性.

关键词: TFSOI RESURF 器件; 表面电场分布; 电势分布; 击穿电压; 优化设计

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