Mode analysis and structure parameter optimization of a novel SiGe-OI rib optical waveguide*

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Abstract: The mode of a novel SiGe-OI optical waveguide is analyzed, and its single-mode conditions are derived. The Ge content and structure parameters of SiGe-OI optical waveguides are respectively optimized. Under an operation wavelength of 1300 nm, the structures of SiGe-OI rib optical waveguides are built and analyzed with Optiwave software, and the optical field and transmission losses of the SiGe-OI rib optical waveguides are analyzed. The optimization results show that when the structure parameters H, h, W are respectively 500 nm, 250 nm, 500 nm and the Ge content is 5%, the total power loss of SiGe-OI rib waveguides is 0.3683 dB/cm considering the loss of radiation outside the waveguides and materials, which is less than the traditional value of 0.5 dB/cm. The analytical technique for SiGe-OI optical waveguides and structure parameters computed by this paper are proved to be accurate and computationally efficient compared with the beam propagation method (BPM) and the experimental results.

Key words: SiGe-OI rib optical waveguides; mode analysis; Ge content; structure parameters

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1. Introduction

SiGe-OI is a new type of material developed from SOI and SiGe; it integrates the advantages of the SOI and SiGe materials, and its prospects are very optimistic, so research of SiGe-OI is at the forefront of the microelectronic field at present. The guide layers of SOI optical waveguides are Si, and the cladding layers are SiO_2 and air, due to the large differences in refractive index between Si (n_{Si} = 3.5), SiO_2 (n_{SiO_2} = 1.5) and air (n_{air} = 1.0); the optical transmission of SOI optical waveguides is highly restricted. So, most of the optical transmission is restricted to the guide layer of SOI optical waveguides, and the light energy of radiation into the outside cladding layer is greatly reduced, thereby the transmission loss of optical waveguides can be significantly reduced, which is very favorable for optical integration and opto-electronic hybrid integration, and furthermore, its technology is fully compatible with Si/SOI CMOS VLSI technology. The applications of strain $Si_{1-x}Ge_x$ materials are expanding, ideas of device design have also changed, and the design and manufacture of the device have changed from "doping engineering" to "band engineering"[1]. The refractive index of Si is 3.5, that of Ge is 4.3, and that of SiGe alloy can be adjusted between these values by changing the Ge content. The refractive indexes for waveguide layers with Ge contents of 10%, 20%, 30%, 40%, 50% and 60% are, respectively, 3.53, 3.58, 3.63, 3.69, 3.76 and 3.83[2]. When the Ge content x is changed, the $Si_{1-x}Ge_x$ alloy band gap also can be changed from 1.12 to 0.7 eV[3]. The Ge contents of SiGe optical waveguides have changed, so it is easy to make the numerical aperture (NA) meet the requirements.

The advantages of SOI and SiGe have been absorbed by SiGe-OI alloy materials, with the refraction of the guide layer materials increased, and the restriction effect is enhanced for optical transmission of SiGe-OI optical waveguides. By adjusting the Ge content, it is easy to make the NA meet the requirements, thus making the NA of SOI optical waveguides not too small. At the same time, SiGe-OI optical waveguides also have the characteristics required by single-mode optical waveguides, such as small transmission loss, large cross-section (the height and width of rib optical waveguides matching the guide layer diameter of single-mode fiber), and an NA that matches the guide layer diameter of single-mode fiber at the optical waveguide input and output. These show that SiGe-OI optical waveguides are ideal integrated optical waveguide materials in this field.

In this paper, modes of novel SiGe-OI optical waveguides are analyzed, the Ge content and structure parameters of SiGe-OI optical waveguides are respectively optimized, the structure of SiGe-OI rib optical waveguides are built and analyzed with Optiwave software, and the optical field and transmission loss of SiGe-OI rib optical waveguides are analyzed. The analytical technique for SiGe-OI optical waveguides and structure parameters computed by this paper is proved to be accurate and computationally efficient compared with the beam propagation method (BPM) and the experimental results.

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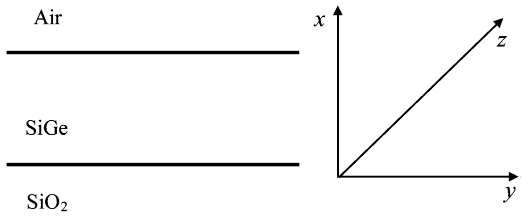

Fig. 1. SiGe-OI optical waveguide.

2. Mode analysis of SiGe-OI optical waveguides

A SiGe-OI optical waveguide is shown in Fig. 1. The refractive index of the waveguide layer is bigger than that of the cladding layer; in the waveguide layer of this optical waveguide, the y-axis and z-axis directions are infinite, and the interface between the waveguide layer and the cladding layer only exists in the direction of the x-axis.

The spatial distribution of electric and magnetic fields are respectively designated $E^0(x, y, z)$ and $H^0(x, y, z)$. Assume that the direction of light spread is in the z-axis direction and the spread constant is designated β. In the x-axis direction, light spread is restrictive, but the distribution of the y-axis direction is the same, so the differential of the y-axis direction is zero, that is, $\frac{\partial}{\partial y} = 0$. According to Ref. [4], the single-mode condition of the SiGe-OI optical waveguide structure is:

$$\tan^{-1}\chi_3\sqrt{a'} < V \leqslant \tan^{-1}\chi_3\sqrt{a'} + \pi. \quad (1)$$

0-order mode of a SiGe-OI optical waveguide has a deadline value, and for TE mode or TM mode, the deadline values of high-order are not the same[4].

If the mode of a SiGe-OI optical waveguide is classified by the spread constant, there are two types of radiation mode. One only radiates to the substrate side, called substrate radiation mode. This mode energy is restricted in the air interface and shows sine changes in the substrate, and it can be excited by optical waveguides. But because its energy continuously radiates from the waveguide layer to the substrate layer when signals are transmitted, its energy will decay out in the short distance.

3. Optimization of SiGe-OI optical waveguides

In order to ensure that optical waveguide production is practical, the following principles must be obeyed in the design: (1) The optical waveguides can carry single-mode; (2) The optical waveguides have a transmission loss of less than 1 dB/cm; (3) The optical waveguides have a large cross-section, and match the guide layer diameter of single-mode fiber; (4) The optical waveguides are close to the NA of single-mode fiber[5].

3.1. Optimization of Ge content

The critical mismatched thickness of SiGe-OI optical waveguides depends on the Ge content x; when x is large, the critical thickness is small. At this time if the thickness of the

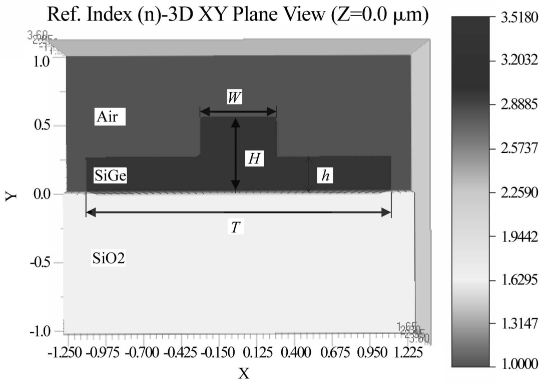

Fig. 2. Structure of SiGe-OI rib optical waveguide.

SiGe-OI optical waveguide is restricted in the area of the critical mismatched thickness, it is far from meeting the requirements of large cross-section, it cannot match the size of the optical fiber, and it is difficult to couple with single-mode fiber. If the thickness of the SiGe-OI optical waveguide is far bigger than the critical mismatched thickness, it is only considered to meet the requirements of large cross-section, and is not restricted by the critical thickness. It is found with electron microscopy analysis that the interface between the SiGe layer and the substrate becomes very rough, and there are a lot of defects and dislocations in the whole epitaxial layer. From the point of view of optical transmission, scattering loss is produced in the wavelength range of optical communication because of mismatch defects and dislocations; this phenomenon is not conducive to low transmission loss of optical waveguides. If the Ge content of a SiGe-OI optical waveguide is too small, the difference of refractive index between epitaxial layer and the substrate is reduced, the model restrictions, especially a high-end model, are reduced, and losses are increased because the guide layer radiation radiates to the substrate. Practical design requires that the optical waveguides not only match the large cross-sections, but also have low transmission losses; the Ge content of SiGe-OI optical waveguides must be optimized.

The NA of $Si_{1-x}Ge_x$-OI optical waveguides is $\sin\phi = [0.18x(7.0 + 0.18x)]^{1/2}$, and the NA of single-mode fiber is 0.2–0.3. In order to match these two values, $\sin\phi$ = 0.2–0.3. It can be estimated that the x value should be in the range of $0.03 \leqslant x \leqslant 0.07$. For integrated consideration, choosing $x = 0.05$, at this point $Si_{0.95}Ge_{0.05}$-OI optical waveguides are matched with fiber, and also have a low transmission loss.

3.2. Optimization of structure parameters

Figure 2 shows the structure of SiGe-OI rib optical waveguides. The substrate material is SiO_2 (n_2 = 1.5), the waveguide layer material is SiGe ($n_1 = 3.5 + 0.18x$), and the cladding layer material is air (n_3 = 1.0).

The inner rib height, outer rib height, and rib width of optical waveguides are respectively recorded as H, h, and W, the effective refractive index is N_1, N_2 in the transmission direction and the effective refractive on the horizontal orientation index is N_3[5]. According to Maxwell theory, let $n_1 > N_2 > n_2 > n_3$, and

$$Y_1^2 = k^2\left(N_2^2 - n_3^2\right),$$
$$Y_2^2 = k^2\left(n_1^2 - N_2^2\right), \tag{2}$$
$$Y_3^2 = k^2\left(N_2^2 - n_2^2\right).$$

Then the plane wave equation TE mode can be expressed as

$$\mathrm{d}^2 E_{y0}(x)/\mathrm{d}^2 x - Y_3^2 E_{y0}(x) = 0, \quad -\infty < x < 0,$$
$$\mathrm{d}^2 E_{y0}(x)/\mathrm{d}^2 x + Y_2^2 E_{y0}(x) = 0, \quad 0 < x < h, \tag{3}$$
$$\mathrm{d}^2 E_{y0}(x)/\mathrm{d}^2 x - Y_1^2 E_{y0}(x) = 0, \quad h < x < \infty.$$

Its solution can be written as

$$E_{y0}(x) = E_c \mathrm{e}^{Y_3 x}, \quad -\infty < x < 0,$$
$$E_{y0}(x) = E_{W1}\cos Y_2 x + E_{W2}\sin Y_2 x, \quad 0 < x < h, \tag{4}$$
$$E_{y0}(x) = aE_\mathrm{c}\mathrm{e}^{-Y_1(x-h)}, \quad h < x < \infty,$$

where E_c, E_W1, E_W2, and a are coefficients that are determined by the conditions, which are continued in the border E_{y0} and $\mathrm{d}E_{y0}/\mathrm{d}x$, and in the border $x = 0$, we have:

$$E_\mathrm{c} = E_\mathrm{W1}, \tag{5}$$

$$Y_3 E_\mathrm{c} = Y_2 E_\mathrm{W2}. \tag{6}$$

In the border $x = h$, we have:

$$E_\mathrm{W1}\cos Y_2 h + E_\mathrm{W2}\sin Y_2 h = aE_\mathrm{c}, \tag{7}$$

$$-Y_2 E_\mathrm{W1}\sin Y_2 h + Y_2 E_\mathrm{W2}\cos Y_2 h = -Y_1 a E_\mathrm{c}. \tag{8}$$

Equation (5) minus Eq. (8) gives Eq. (9):

$$\frac{Y_3}{Y_1}\cos Y_2 h - \frac{Y_2}{Y_1}\sin Y_2 h + \frac{Y_3}{Y_2}\sin Y_2 h + \cos Y_2 h = 0. \tag{9}$$

From Eqs. (2) and (9), N_2 can be obtained with the iteration method, which changes with thickness h. Using the same method, N_1 can be obtained, which changes with thickness H. From two-dimensional optical waveguide theory it is known that if single-mode is transferred in optical waveguides, the refractive index of the waveguide layer must be higher than both sides, and at the same time the effective refractive index of the waveguide layer is the only one. Obviously, when $h \geqslant H$ cannot be the optical waveguides, which would require $H > h$, the N_1 value is unique after h is identified. After H and h are selected, N_1 and N_2 are identified. $n_1 = n_3 = N_2$, $n_2 = N_1$, $H = W$, $N_2 = N_3$ are inserted into the relevant equation, and the effective refractive index is calculated, and then this can be inserted into the plane wave equation of the TE model. According to Maxwell theory, the effective refractive index N_3 is available with the Matrix elimination method and the numerical iteration method. In order to reduce the coupling loss, we hope that the shape of rib optical waveguide is square; that is, the size of W is closer to H. The preferred structural parameters are H = 500 nm, h = 250 nm, W = 500 nm.

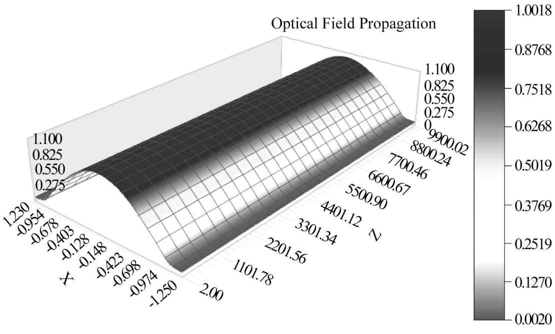

Fig. 3. 3D optical field intensity.

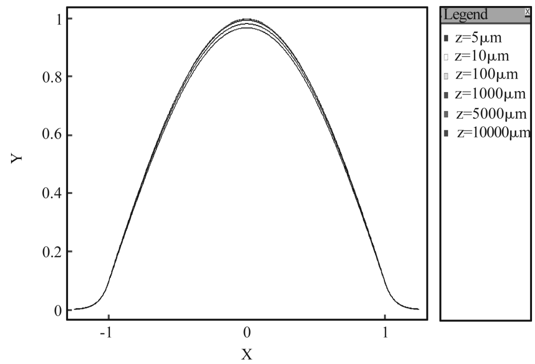

Fig. 4. Optical field section along the Z axes.

4. Simulation and verification

Models of the SiGe-OI rib optical waveguides are built by Optiwave software (small capitals type software, which can efficiently analyze optical waveguides and fibers) based on theoretical analysis and calculations of SiGe-OI rib optical wave-guides. In the simulation at 1.3 μm wavelength the optical field and transmission loss of the SiGe-OI rib optical waveguides are analyzed.

Figure 3 shows the three-dimensional optical field intensity. From this figure, we can see that light is basically limited to $T = 2$ μm in the x-axis direction, and the closer to center it is, the stronger optical field intensity. As the light transmission distance increases in the z-axis direction, from the colors we cannot easily see the optical field intensity change. Figure 4 shows the optical field section along z axes. From Fig. 4 we can see that, as the z-axis increases, that is, the transmission distance increases, the optical field intensity is decreased, but the decrease rate is not great.

In the media waveguide, loss due to the processes of absorption, scattering and other reasons caused by power loss in the course of waveguide transmission is known as the waveguide loss. The power loss coefficient 2α can expressed as[6]

$$2\alpha = 10\left[\lg P(z_1) - \lg P(z_2)\right]/(z_1 - z_2), \tag{10}$$

where z_1 and z_2 are the distance of any two points along the spread direction, in units of cm. The unit of power loss coeff-

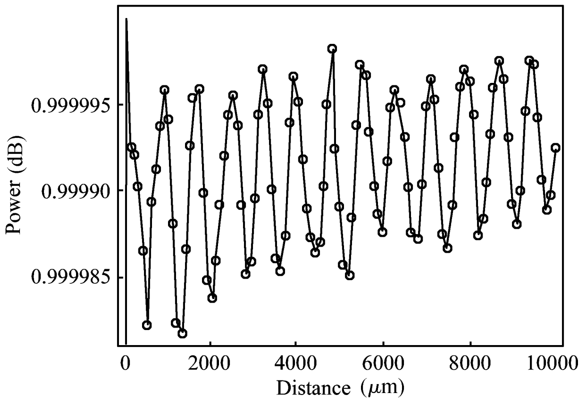

Fig. 5. Power versus distance under ideal conditions.

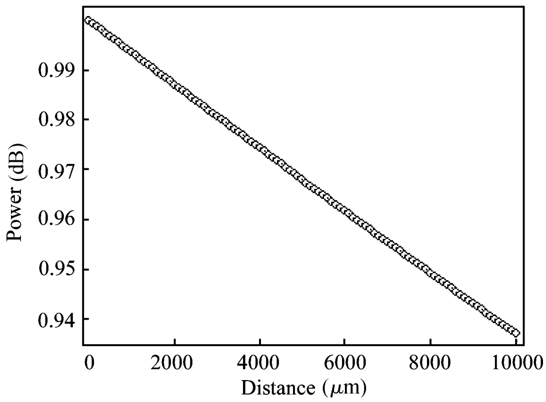

Fig. 6. Power versus distance with radiation power loss.

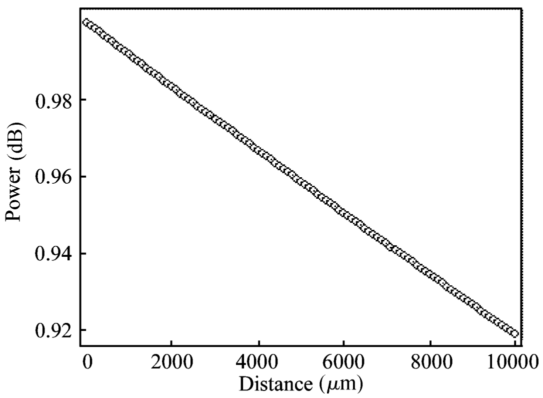

Fig. 7. Power versus distance considering the material power loss.

icient 2α is dB/cm. In integrated optics, the general requirement for the power loss of media is below 1 dB/cm.

When simulated with this software, the power losses of the radiation outside the waveguides and materials can all be considered, and we simulated the power losses of SiGe-OI optical waveguides under different conditions, as shown in Figs. 5, 6 and 7. In these figures, the distance units are μm, the initial distance is 0 μm; the power units are dB, the initial power is 1 dB.

The relationship of SiGe-OI optical waveguide power loss and transmission distance under ideal conditions is shown in Fig. 5. From this figure we can see that the power loss is 3.2957×10^{-5} dB/cm with Eq. (10).

Taking the power loss of the radiation outside the waveguides into account, the relationship of SiGe-OI optical wave-

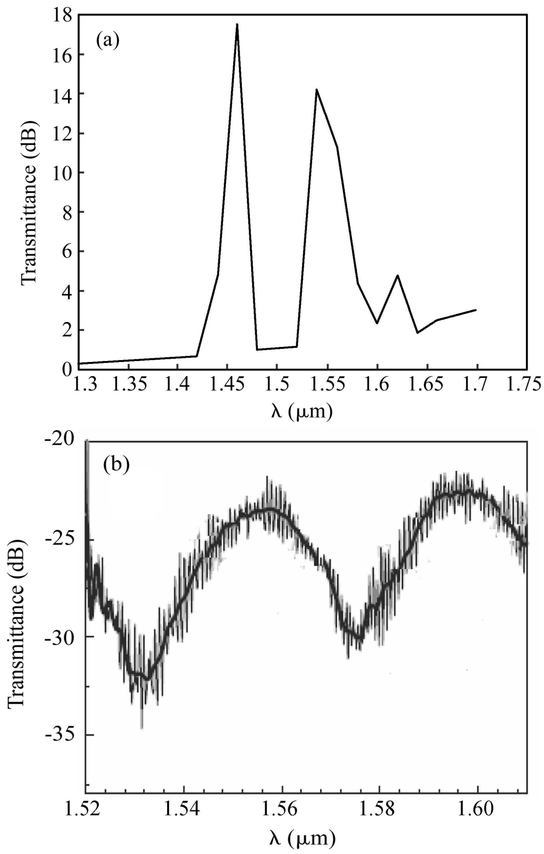

Fig. 8. Relationship of transmission loss and wavelength of optical waveguides: (a) Simulated; (b) Measured[8].

guide power loss and transmission distance is shown in Fig. 6. Inserting the data into Eq. (10) gives a power loss value of 0.2821 dB/cm.

From the above description we know that the index of the $Si_{0.95}Ge_{0.05}$ layer is 3.5036; when the power loss of materials is considered, the index of the $Si_{0.95}Ge_{0.05}$ layer is reduced to 3.4554. Figure 7 shows the relationship of SiGe-OI optical waveguide power loss and transmission distance, and the value of the power loss is 0.3683 dB/cm with Eq. (10).

From Figs. 5, 6 and 7 we can see that the loss of the radiation outside the waveguides is 0.2821 dB/cm, and that of the materials is 0.08623 dB/cm. So the total loss is 0.3683 dB/cm, less than 0.5 dB/cm of the traditional low-loss optical waveguides[7].

Because SiGe-OI material is still in the experimental phase of exploration at present, there are no finished SiGe-OI optical waveguide products. From the structure and principles, the characteristics of SOI optical waveguides are closest to SiGe-OI optical waveguides, so the analytical technique for SiGe-OI optical waveguides and structure parameters computed by this paper is proved to be accurate and computationally efficient when the simulation curve of SiGe-OI optical waveguides and the measured curve of SOI optical waveguides are compared. Figure 8 shows the relationship of transmission loss and transmission optical wavelength for simulated SiGe-OI optical waveguides and the measured SOI optical waveguides[8]. From the figure we can see that the transmis-

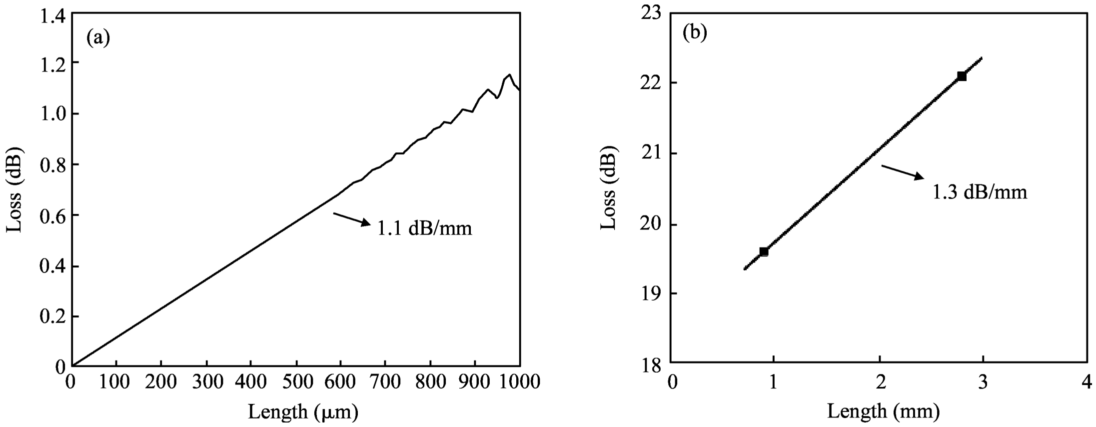

Fig. 9. Relationship of transmission loss and transmission distance of optical waveguides: (a) Simulated; (b) Measured[8].

sion loss fluctuates in transmission with different transmission wavelengths.

Figure 9 shows the relationship of transmission loss and transmission distance for simulated SiGe-OI optical waveguides and measured SOI optical wave-guides. As transmission distance increases, transmission loss also increases. At a wavelength of 1.52 μm, the simulated transmission loss of SiGe-OI optical waveguides is 1.1 dB/mm, smaller than the measured value of 1.3 dB/mm.

5. Conclusions

In this paper, the modes of novel SiGe-OI optical waveguides are analyzed, and the single-mode conditions of SiGe-OI optical waveguides are derived. According to the practical optical waveguide production rules, Ge content and structure parameters of SiGe-OI optical waveguides are respectively optimized. Under an operation wavelength of 1300 nm, the structure and model of SiGe-OI rib optical waveguides are built and analyzed with optiwave software, and the optical field and transmission loss of SiGe-OI rib optical waveguides are analyzed. The optimization results show that when the structure parameters H, h, W are respectively 500 nm, 250 nm, 500 nm and Ge content is 5%, the total power loss of a SiGe-OI rib waveguide is 0.3683 dB/cm considering the radiation loss outside the waveguides and materials, which is less than the traditional value of 0.5 dB/cm. The analytical technique for SiGe-OI optical waveguides and structure parameters computed by this paper is proved to be accurate and computationally efficient when compared with the beam propagation method (BPM) and experimental results. So using this method, excellent performance low-loss optical waveguides will be obtained in the future.

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