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Study and Analysis of SBD Detector Sensitivity Based on Au-InP and Au-GaAs Structures

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In this paper, a novel approach of materials combination is proposed to enhance the performance of Schottky Barrier Diodes (SBD) detector. High purity of gold (90 %) in combination with two different semiconductors (Indium Phosphide (InP) and Gallium Arsenide (GaAs)) are used to perform SBD samples. The current saturation and ideality factor were extracted from experimental current-voltage characterization, the results insure interesting values. Our sample's conductivity has been studied and confirm asymmetric in its shape. The analysis of maximum level of current sensitivity for both samples prove their peak value in the nonlinear range of SBD, thus Au-InP gives maximum sensitivity equal to 27.96 A/W and Au-GaAs has a maximum sensitivity equal to 49.33 A/W, which makes them successfully useful for detection in comparison to other works in this domain.

Keywords: SBD, Sensitivity, Detection, Characterization.

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1. INTRODUCTION

Nowadays wireless propagation and radio technology offer new services, promise better quality, insure transmission reliability and facilitate the apparition of various applications. The process of detection presents an essential stage in these evolutions; it is fundamentally based on nonlinear components to achieve the detection of Radio Frequency (RF) signals [1]. For their strong electrical nonlinearity and simplicity in fabrication and packaging, SBD have been used to implement RF detector for the past century and continue to be a good candidate to achieve the detection with high sensitivity [2, 3]. SBD is used as detector in various applications and several domains such as remote detection, imagery by satellite and radio astronomy, they also equip automotive radars [4]. In fact, the understanding of physics that joins different aspects (the structure, the physical properties and the characterization of materials) is primordial in these technological domains. Researchers extend their work to meet the criteria of modern technology using semiconductors with very high performance, leading to improve more electronic devices [5]. This is the case for SBD detector where the evolution of Group III-V semiconductors technology is behind its advancement [6]. In this work, we are especially interesting on GaAs and InP. These two mentioned materials have many advantages compared to Silicon, taken in consideration their large band gap, high saturation velocity, high electron mobility, and break down voltage [7].

The objective of this work is to estimate the performance of SBD detector based on suitable materials combination. Moreover, checking nonlinearity of current-voltage characterization and asymmetric in conductivity, then determine the maximum sensitivity level that can be achieved.

2. MATERIALS AND METHODS

In this work, the samples selected to perform SBD detector are based on gold (Au) as metal, which has high work function value (5.12 Ev) [8]. We have chosen InP and GaAs from III-V semiconductors compound to realize the junction with Au.

The samples formed are Au-GaAs and Au-InP, they are circular planar diodes with an average radius of 0.5 µm and 0.6 µm respectively. Their junction capacity equal to 8 fF and 15 fF respectively. Doping density of both samples equal to 5 10^{17} cm^{-3}. Fig. 1 show a cross section of our model structure of SBD.

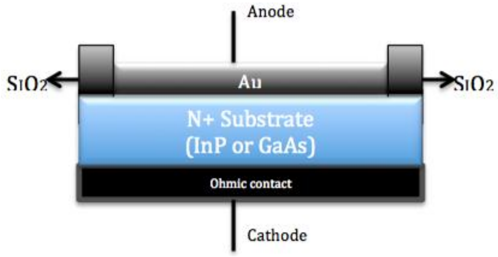


Fig. 1 – Structure of Schottky barrier diode detector

We proceed the operation of sputtering to our samples to insure maximum resolution analysis using Scanning Electron Microscopy (SEM), this operation serves to deposit a thin-film layer on the sample by ejecting particles from a solid target material due to bombardment of the target by energetic particles, in the general case the target may be made of gold but it can also be made of Carbon or even another metal. In the laboratory, a rare gas is used to extract atoms from the target and cold water circulates around the specimen to maintain it at room temperature.

3. PROCESS OF DETECTION

To detect weak RF signals in any system of transmission, it is necessary to conceive the appropriate equipment that assures this task as efficiently as possible. The function of wave detection is fundamentally achieved by nonlinear component where the nonlinearity is the key element in the process of detection. In fact, SBD detector produces the highest detector performance in comparison to other nonlinear components [9]. The principle consists to convert low level signal (input signal) from one frequency to another. SBD detector has three accesses; one for the input signal and an additional input represents optional DC bias. The third access is for the output signal presents the detected signal [1].

3.1 Current-Voltage Characteristics

The overall charge transport mechanism over metal-semiconductor junction is dominated by the thermionic emission. So that the current is related to voltage by the relationship given by [10].

$$I = I_s \exp(\frac{qV}{\eta KT} - 1) \quad (3.1)$$

$$I_S = AA^*T^2\left(e^{\frac{-q\phi b}{kT}}\right) \quad (3.2)$$

Where I_S is reverse saturation current, q is elementary charge (1.6×10^{-19}C), η is the ideality factor, A is junction area, A^* is effective Richardson constant, T is absolute temperature, ϕb is the barrier height, k is Boltzmann's constant.

Fig. 2 illustrates the conventional equivalent circuit for SBD mounted in a package. Where L_p is the lead inductance, R_s is the diode series resistance, R_j is the junction resistance, C_j is the junction capacitance and C_p is the package capacitance [10].

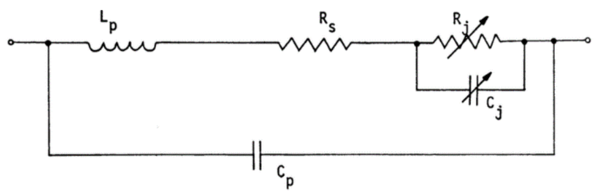


Fig. 2 – Equivalent Circuit for SBD

Equation (01) neglects the diode series resistance, which becomes dominant at high forward bias voltages. By the introduction of IR_s term, we can pass from the first order model to the second order model, given as follows (3).

$$\mathrm{I} = \mathrm{I_s} \exp\left(\frac{\mathrm{q(V - IR_s)}}{\mathrm{\eta kT}} - 1\right) \quad (3.3)$$

3.2 Square Law of Detection

Expression of thermionic emission is estimated by a Taylor series expansion, giving by equation (3.4) [11].

$$\mathrm{I_S}[\,\mathrm{Exp}(\frac{\mathrm{V}}{\mathrm{v_t}} - 1)] = \mathrm{I_S}[\,(\frac{\mathrm{V}}{\mathrm{v_t}} + 1/2\left(\frac{\mathrm{V}}{\mathrm{v_t}}\right)^2 + \cdots] \quad (3.4)$$

$$\mathrm{I} = \frac{\mathrm{I_S}\, v}{\mathrm{v_t}}\cos(\omega t) + \frac{\mathrm{I_S}}{4}\left(\frac{v}{\mathrm{v_t}}\right)^2 [1 + \cos(2\omega t)] + \quad (3.5)$$

Assuming v_t is the thermal voltage defined by $v_t = \eta KT/q$ and the input signal V is $V = v\cos(\omega t)$. The current across SBD detector is than describe by expression (3.5), which is composed of three dominant terms, the fundamental, the second harmonic of the input signal generally bypassed by a capacitor, and the third term represents the detected signal (I_{dc}) proportional to the square of the input voltage.

$$\mathrm{I_{dc}} = \frac{\mathrm{I_S}}{4}\,(\frac{v}{\mathrm{v_t}})^2 \quad (3.6)$$

3.3 Sensitivity of SBD Detector

Sensitivity is quite useful in designing SBD detector because it defines the level of incident energy required to produce voltage or current at the output. It has the units of Amp/Watt or Volt/Watt. Sensitivity (S) is defined as the ratio of I_{dc} to the incident energy (P_{in}) to the junction [12], the current detected given by equation (3.6) can be written as:

$$I_{dc} = \frac{1}{4}v^2 f''(V). \quad (3.7)$$

Where $f''(V)$ is the second derivative of current with respect to voltage. The incident energy to the junction is given by the expression bellow.

$$P_{in} = \frac{1}{2}v^2 f'(V). \quad (3.8)$$

Where $f'(V)$ is the first derivative of current with respect to voltage. Therefore, the current sensitivity, S_i, is defined as

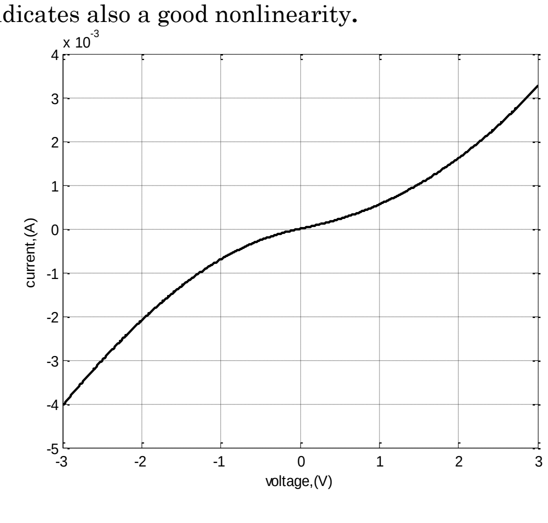
$$S_i = \frac{1}{2}\frac{f''(\mathrm{V})}{f'(V)} = \frac{dI^2/dV^2}{2dI/dV} \quad (3.9)$$

The current sensitivity can be converted into voltage sensitivity, by using the relationship: $S_v = S_i\mathrm{R}_j$. Where R_j presents the junction resistance, it is given by $R_j = \partial V/\partial I$. Therefore, the voltage sensitivity (S_v) is defined as

$$\mathrm{S}_v = \frac{dI^2/dV^2}{(2dI/dV)^2} = \frac{1}{2I_s\, e^{\frac{qV}{nKT}}} = \frac{1}{2(I + I_s)} \quad (3.10)$$

4. RESULTS AND DISCUSSION

The use of spectrum analyzer allowed to plot the variation of current versus voltage values. Fig. 3(a) illustrates I-V characteristics of Au-InP sample, the curve exhibits a strong nonlinearity making SBD device useful for detection. For I-V characteristics of Au-GaAs sample, shown in Fig. 4(a), the curve indicates also a good nonlinearity.



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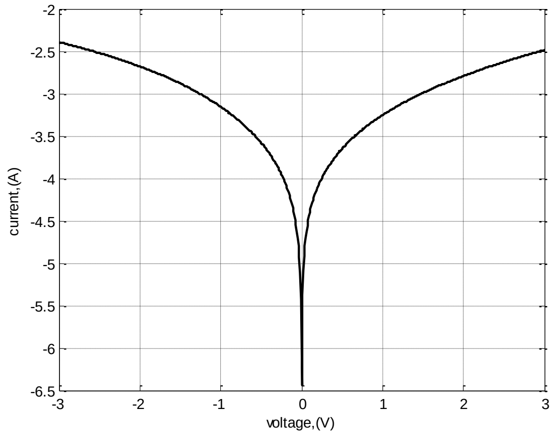
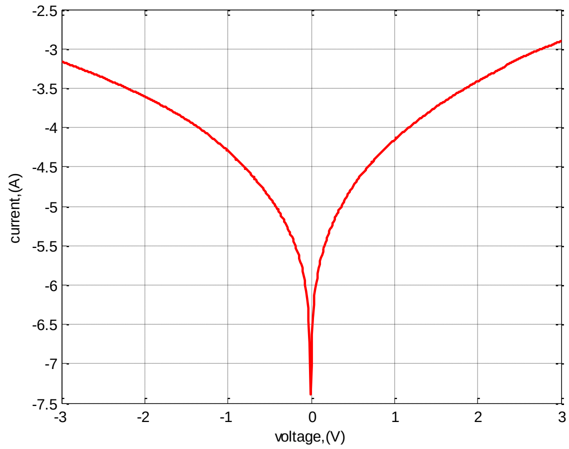


b

Fig. 3 – Experimental current-voltage characterization of Au-InP Schottky diode (a) in a linear (b) and a semi-logarithmic illustration



b

Fig. 4 – Experimental current-voltage characterization of of Au-GaAs Schottky diode (a) in a linear (b) and a semi-logarithmic illustration

Our next task is to find saturation current and ideality factor which are predominant parameters to characterize SBD detector. For low bias voltages, the voltage IR_s is neglected to V. Thus, the values of I_S and η can be determined from the intercept and the slope of linear region respectively using semi-logarithmic curve of *I-V* shown in Fig. 3b and Fig. 4b [13].

The values of I_S and η are indicated in Table 1. For the thermionic emission mechanism, the ideality factor in the current-voltage relation is closed to unity. However, in practice the ideality factor departs from unity due to the influence of other mechanisms like tunnelling current [14].

The ratio of sensitivity defines the nonlinearity of SBD detector and hence its performance. The first derivative $f'(V)$ of current defines the conductivity of SBD and the second derivative $f''(V)$ is the rate of change of conductivity. Fig. 5 and Fig. 6 show the conductivity versus voltage for Au-Inp and Au-GaAs detectors respectively. Both curves confirm asymmetric shape of conductivity; even the shape of conductivity is not the same for both SBD detectors. The minimum conductivity value is obtained in reverse bias region and the maximum value in forward bias. These observations are similar to those found by Brinkman and all [15] explained by the difference between work functions of materials used.

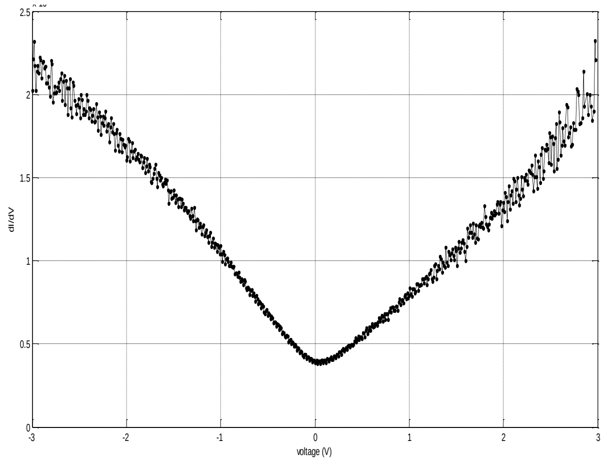


Fig. 5 – SBD conductivity versus DC Bias of Au-InP

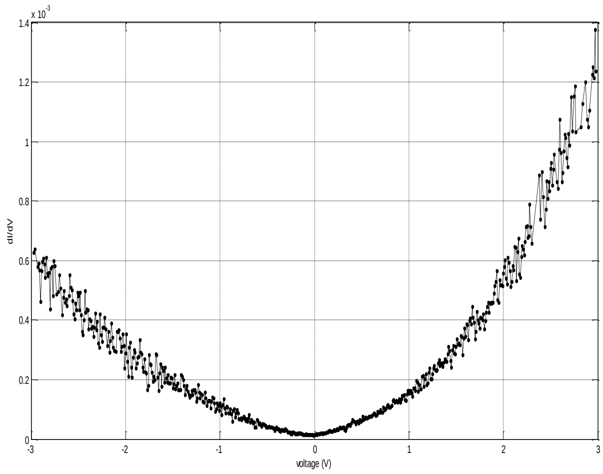
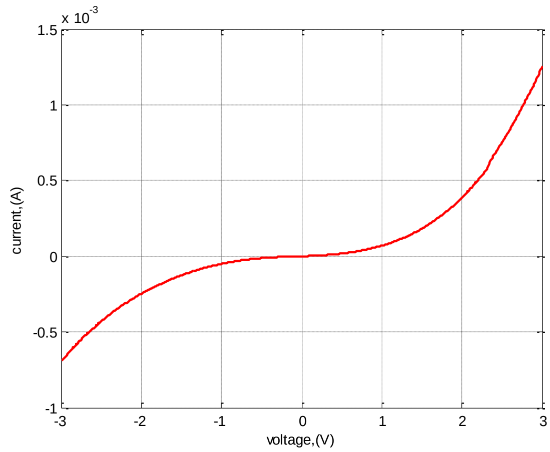


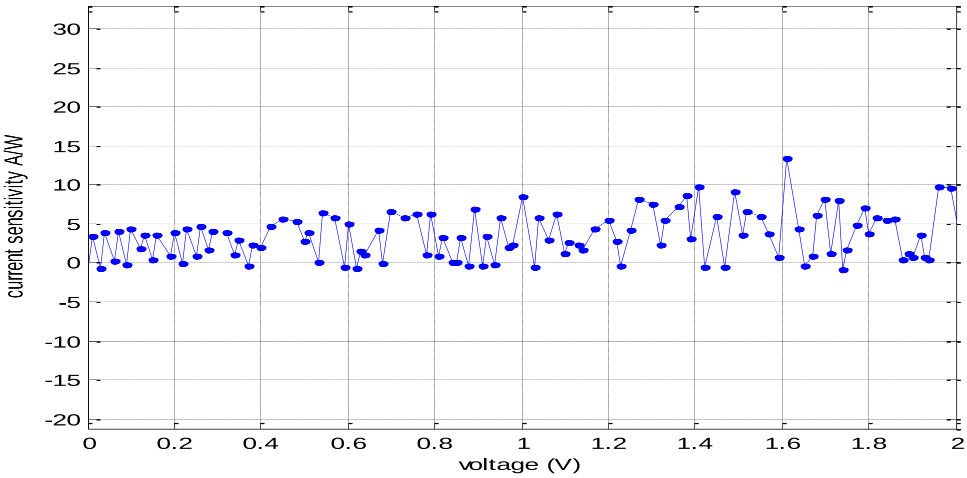
Fig. 6 – SBD conductivity versus DC Bias of Au-GaAs



a

The sensitivity level of SBD detector according to voltage values shown in Fig. 7 and Fig. 8 measured at room temperature. We started this study by fitting S_i versus low forward (from 0 to 2V) bias for Au-InP and Au-GaAs, which are illustrated in Fig. 7(a) and Fig. 8(a) respectively. Then we extended the study to plot S_i

versus high values of forward bias (from 2 to 3V) for both samples. Shown in Fig. 7(b) and Fig. 8(b).Knowing that the maximum value of sensitivity occurs when the dc bias gives the peak curvature of S_i versus V [16]. These results allow us to prove that the sensitivity level of our samples does not exceed a significant level at very low. forward voltage. Whereas, when SBD detector exhibits high forward voltage and strong nonlinearity the level of sensitivity has a relatively large value. This is the case for Au-InP where $S_i = 27.96$ A/W at 2.84 V and for Au-GaAs where $S_i = 49.33$ A/W at 2.82 V.



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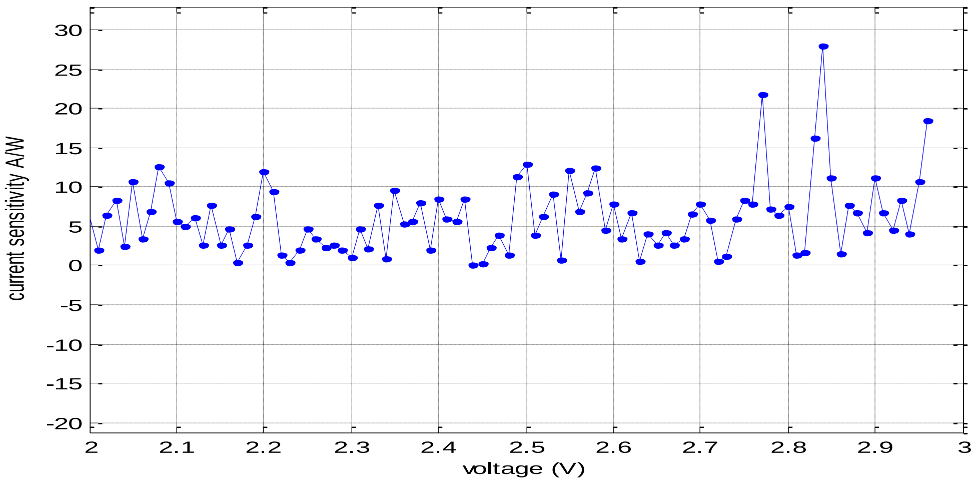
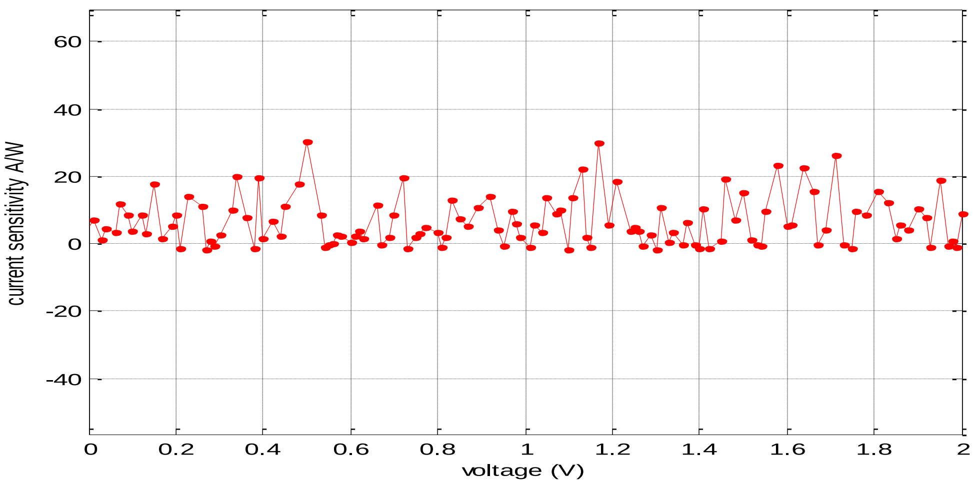


b

Fig. 7 – SBD sensitivity versus DC Bias of Au-InP (a) Low values of forward bias, (b) High values of forward bias



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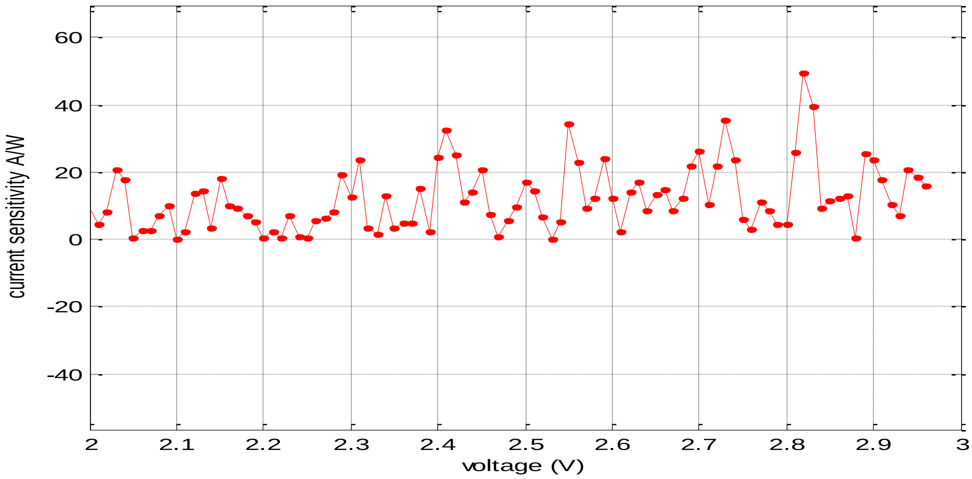

b

Fig. 8 – SBD sensitivity versus DC Bias of Au-GaAs. (a) Low values of forward bias, (b) High values of forward bias

It should be noted that from expression (3.10), the maximum value of S_v occurs when the polarization of the diode approaches zero. This condition cannot be verified in practice, which favors the use of SBD detectors as Zero Bias Diode (ZBD) detector. However, the use of SBD in current mode offered significant values of S_i rather than used in voltage mode.

Table 1 – Summary of experimental values

Parameters	Au-InP (this work)	Au-GaAs (this work)	[11] a,*	[02] *
I_s (μA)	4.17	0.22	/	5 10 -2
η	1.31	1.45	/	1.35
C_j (fF)	8	15	12	10
R_s (Ω)	15	65	2.9 10 -3	8
S_i (A/W)	27.96	49.33	12.03	10

* Values of S_i do not occur in the same value of voltage.
a the best value of S_i is taken.

5. CONCLUSION

The type of materials selected in this work to form SBD detector structure insures important value of sensitivity and gives satisfactory parameters values of SBD detector, as well as the asymmetry in conductivity. These benefits encourage manufacturers to adopt this combination to realize successful SBD detector for various applications. On the other hand, several works must be elaborated particularly on coupling between antenna and detection system to eradicate the losses of signals and accordingly improve sensitivity.

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