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An Improved CMOS Sensor Circuit Using Parasitic Bipolar Junction Transistors for Monitoring the Freshness of Perishables

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Abstract: This paper presents an improved integrated circuit sensor for emulating and monitoring the quality of perishable goods based on the surrounding temperature. The sensor is attached to the container of fresh or preserved farm or marine produce and passes on the monitored quality information from manufacturer/producer to the consumers. The sensor essentially emulates the thermal deterioration caused by the environment on its way from producer to consumer and provides a readout indicating the freshness of the goods. Compared to previous designs, parasitic substrate PNP devices in standard CMOS process instead of subthreshold MOS devices are used for emulating the activation energy of degradation (spoiling) chemical reactions. The reliability of the sensor is thus considerably enhanced compared to previous design. In addition, an analog squaring circuit is used for emulating the degradation for large activation energy thereby removing the need for a multiplier in the digital processing section and hence reducing silicon area. Simulations were carried out using a 0.18 µm TSMC CMOS process technology. The power consumed by the sensor was around 16 mW. *Copyright © 2008 IFSA.*

Keywords: Food sensor, CMOS sensor, Parasitic bipolar devices, Freshness, Analog integrated circuits.

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1. Introduction

Monitoring the degradation of perishables during distribution from producer to consumer is an essential procedure in assuring acceptable quality of most farm/marine food products. On the other hand, producers have no prior knowledge of the conditions of distribution. As the perishables/goods may be distributed under suitable or unsuitable environmental conditions, the producers are forced to set conservative expiration dates of the products. As a result, considerable amount of perishables are often thrown away (wasted) since the expiration date has already passed, although the goods are still edible. Hence, accurate monitoring of the degradation of perishables can help in food conservation. This monitoring can be carried out by electronically emulating the thermally initiated chemical reaction that causes the degradation of the perishables. Such an emulation sensor would be attached to the perishables and carried along during the goods distribution process. It is thus subjected to the same environmental variations for the perishables and emulates the degradation of the perishables caused by the surrounding environment. By reading the calibrated output of the sensor the consumer can accurately ascertain the amount of freshness remaining in the perishable.

In previous work [1], [2] sub-threshold devices are used for emulating the activation energy of chemical reactions and a digital multiplier is used to improve the dynamic range to account for high activation energy (0.4 eV-0.5 eV) [4] of most spoiling bio-chemical reactions. In this work, parasitic bipolar PNP devices are used for emulating the activation energy, thereby, considerably enhancing the reliability of the sensor. Also, an analog squaring circuit is used to increase the dynamic range of the sensor to account for large activation energy of most degradation chemical reactions in spoilage. Higher reliability can thus be achieved using this design at the cost of higher power dissipation. Preliminary work on this proposed sensor circuit was reported in [9].

2. Emulation of the Degradation Process Using Parasitic PNP Devices as Thermosensor

The degradation of perishables is a bio-chemical reaction between concentrations of two constituents; one of which is the perishable good (say, A) and the other is usually air/oxygen (say, B). The concentration of the resulting spoiling substance (say, C) is usually given by [1], [2],

$$[C] = [A]_0 [B]_0 k_0 \int_0^{t1} e^{\left(-\frac{E_a}{k_B T}\right)} dt \,, \tag{1}$$

where, $[A]_0$ and $[B]_0$ are initial concentrations of A and B and $[C]$ corresponds to the concentration of the spoiling substance [10]. E_a is the activation energy for the chemical reaction, k_0 is a constant of proportionality, k_B is the Boltzmann constant and T is the temperature of the surrounding environment in °K. For the same activation energy, higher temperature results in a larger temporal integration with the consequence of larger concentration of spoiling substance and reduced freshness of the food products. In order to emulate the deterioration of the freshness of the perishables, use of the parasitic lateral PNP transistor of a standard CMOS (Complementary Metal Oxide Semiconductor) process (as a thermo-sensor) as shown in Fig. 1, is proposed in this paper instead of the sub-threshold NMOS device in [1], [2]. The collector current of this parasitic PNP device I_C is given by,

$$I_C = I_S e^{\frac{q v_{EB}}{\eta K_B T}} \,, \tag{2}$$

where I_S and η are process dependent parameters [5]; v_{EB} is the emitter-base voltage; q is the elementary charge. To set the activation energy for emulating a degradation process, two PNP transistor (PNP1 and PNP2) of similar geometry (same fixed emitter area) are biased by two different dc base voltages vb1 and vb2 (applied by external user control), and, the ratio of their collector currents is taken. Then this ratio is given by,

$$\frac{I_{C2}}{I_{C1}} = e^{-\frac{q(V_{EB1}-V_{EB2})}{\eta K_B T}} = e^{-\frac{E_0}{K_B T}}, \tag{3}$$

where

$$E_0 = \frac{q(V_{B2}-V_{B1})}{\eta} \tag{4}$$

Here E_0 is the sensor emulated activation energy of the spoiling chemical reaction. By integrating equation (3) over time, we have,

$$\int_0^{t1}\left(\frac{I_{C2}}{I_{C1}}\right)dt = \int_0^{t1} e^{-\frac{E_0}{K_B T}}dt \tag{5}$$

Equation (5) is thus an electronic equivalent of the spoiling reaction given by equation (1).

For a PNP device reasonable currents can be obtained for V_{BE} varying between 0.45 V to 0.85 V and hence activation energy of up to 0.4 eV can be emulated compared to MOSFET in sub-threshold operation. In addition an analog squaring circuit can be used in down stream sensor path to emulate large activation energies. As a result, activation energies between 0.1 eV to 0.8 eV [4] can be emulated by this proposed circuit using less total hardware compared to [1], [2].

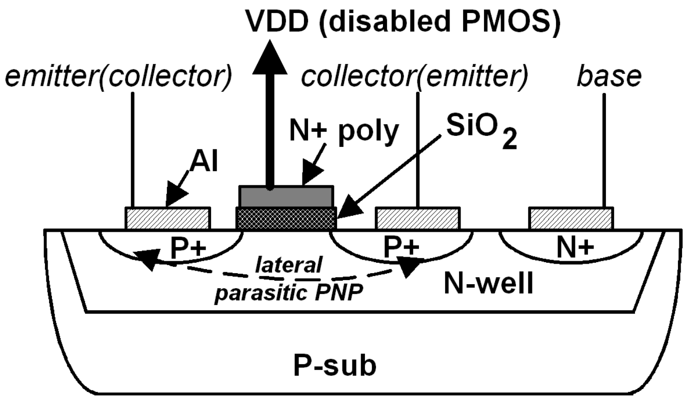

Fig. 1. Cross-section of a lateral parasitic PNP device in a standard CMOS process (used as thermo-sensor) obtained by disabling the PMOS device (with gate tied to the supply voltage VDD).

3. Description of the Proposed Sensor Circuit

Fig. 2 shows the complete circuit diagram of the analog front-end of the sensor consisting of three blocks, (a) the bipolar thermo-sensor and the trans-linear divider in the top, (b) the squaring circuit in the middle and (c) the current controlled ring oscillator in the bottom. The thermo-sensor consists of two PNPs (PNP1 and PNP2) and produces two drain (collector) currents I_{DM21} and I_{DM22}.These two currents are passed to the trans-linear divider which calculate the ratio, $\frac{I_{C2}}{I_{C1}}$ given by equation (3) thereby emulating the degradation rate for the given activation energy. The sensor activation energy can be varied for different category of perishables by changing the bias voltages at the two thermo-sensor PNP bases which can be implemented by external control. The output of the trans-linear divider is feed into the squaring circuit using the current mirror consisting of the devices M14, M15, M16, M25 and M26. The squaring circuit then doubles the activation energy to account for slowly degrading perishables. Next, the current controlled oscillator is biased by the output current of the squaring circuit using the current mirror formed by the devices M35, M36, M37, M38, M39, M40, M41, M42, M53, M54, M55, M56 and M57. The ring oscillator produces oscillation pulses with frequency, *f* proportional to this current. The PMOS devices in the oscillator are made twice the width of the NMOS devices in order to compensate for the slower hole mobility, so that, the rise-time and fall-time of the oscillation pulses are nearly equal.

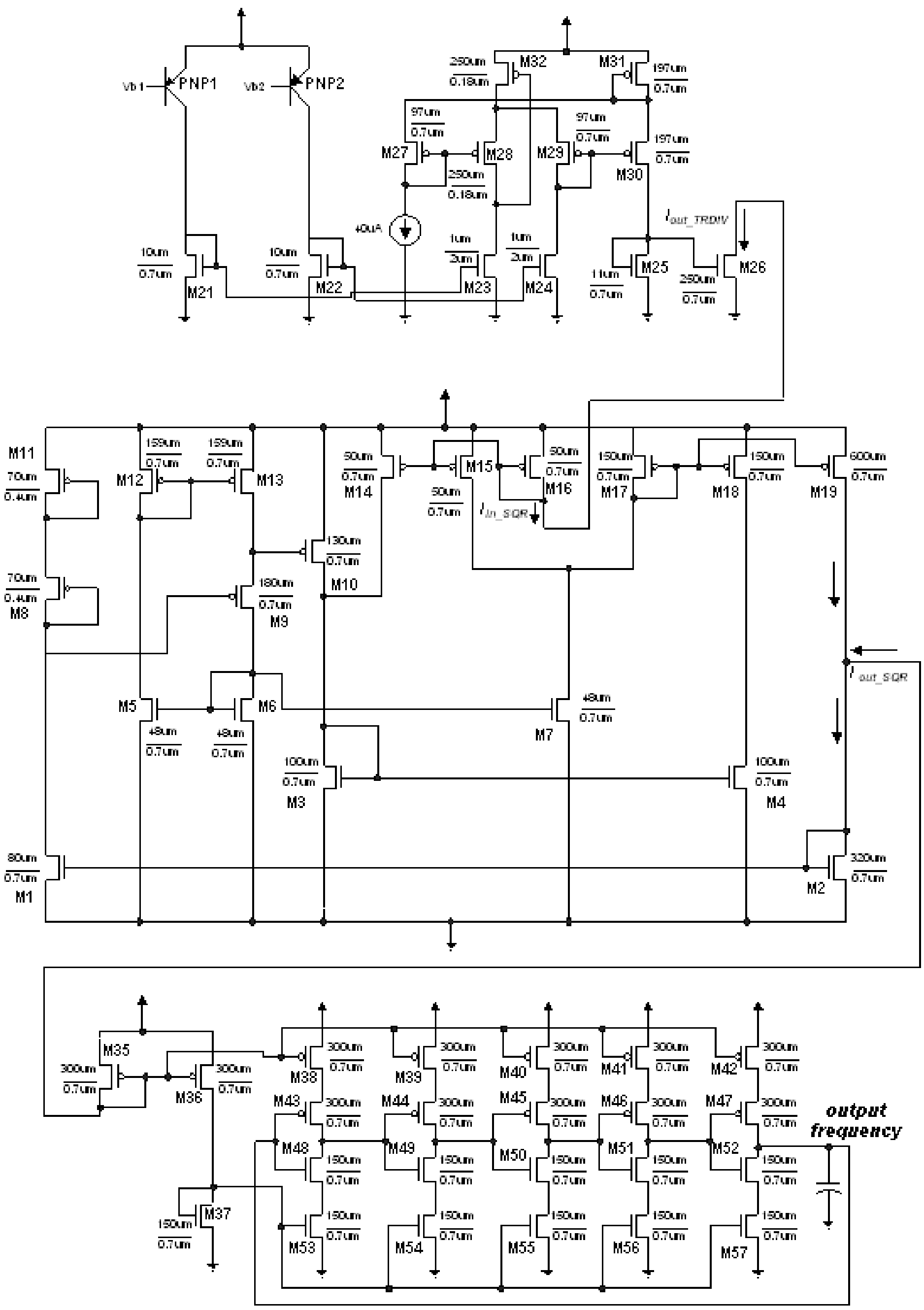

Fig. 2. Circuit diagram of the analog front-end of the quality sensor consisting of forward-active PNP thermo-sensor, strong inversion trans-linear divider circuit, squaring circuit and current controlled 5-stage ring oscillator.

Fig. 3 shows the digital backend of the sensor. It essentially consists of a temporally resetable up-counter, a count register, an accumulator and a control circuit. The accumulator consists of an adder and feed-back register. The registers are built using Delay-Flip-Flops (D-FFs), the counters are designed using Set-Reset Toggle-Flip-Flops (T-FFs) and the Adder is designed using 8 4-bit carry-look-ahead full-adder stages. The digital up-counter counts the number of pulses for fixed short periods of time Δt, which is proportional to the frequency *f* of the ring oscillator. A higher count indicates higher temperature and higher degradation of the perishables. These counts over the short periods Δt are next accumulated by the adder-accumulator block. The total count in this accumulator output indicates how much freshness has been lost from the perishable goods. Consequently, exposure to higher temperatures during a given period of transportation and distribution of the perishables before consumption by end customer, hastens (brings closer) the expiration date.

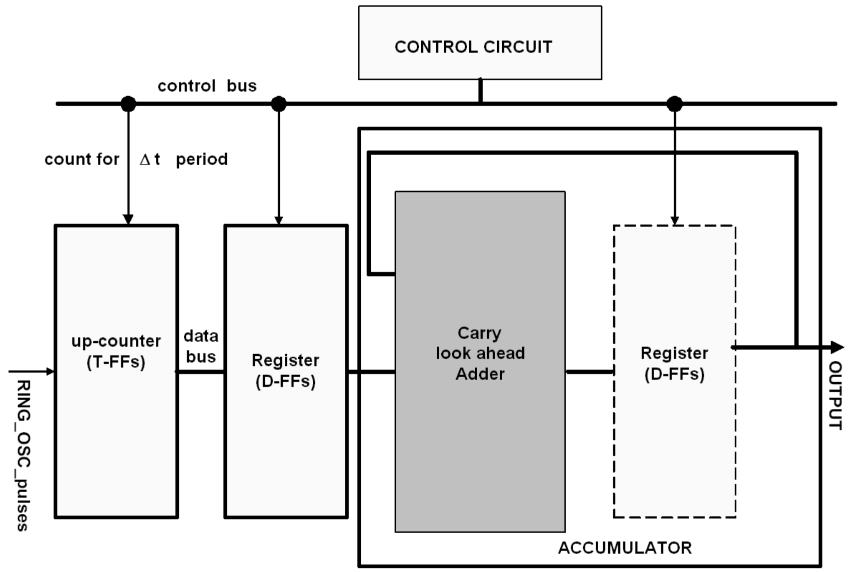

Fig. 3. Digital back-end of the quality emulating sensor consisting of counter, input register, accumulator (adder and output register) and a control input.

The CMOS trans-linear divider [6], [7], [8] (using a reference current of 40 μA) works in the saturation QTL [8] (Quadratic trans-linear) region. The gate-to-source voltages of the MOSFETs (M27, M28, M29 and M30) in Fig. 2 form a closed loop. Then based on the trans-linear principle [6], [7], [8] the output current of the trans-linear circuit is given by,

$$I_{OUT\_TRDIV} = I_{REF}\frac{I_{C2}}{I_{C1}} = I_{REF} * e^{-\frac{E_o}{K_B T}} \tag{6}$$

Next, the bias current for the ring oscillator, produced by the analog current squarer [3], is given by,

$$I_{OUT\_SQR} = I_{REF}^2 * e^{-\frac{2E_o}{K_B T}} \tag{7}$$

As illustrated in Fig. 2, the current controlled oscillator is a five stage ring oscillator, whose frequency of oscillation [1] is given by,

$$f = \frac{I_{OUT\_SQR}}{2mC_L Vdd} = \frac{I_{REF}^2}{2mC_L Vdd} e^{-\frac{2E_o}{K_B T}}, \tag{8}$$

where, m is 5 in this case for the 5-stage ring oscillator, C_L is the load at the output of each inverter, with *Vdd* being the supply voltage.

The output of the up-counter during every Δt period is given by,

$$\int_t^{t+\Delta t} f dt = \int_t^{t+\Delta t} \frac{I_{REF}^2}{2mC_L Vdd} e^{-\frac{2E_o}{K_B T}} dt \tag{9}$$

And, finally the accumulated content at time t1 is given by,

$$final\_output = \frac{I_{REF}^2}{2mC_L Vdd} \int_0^{t1} e^{-\frac{2E_o}{K_B T}} dt \tag{10}$$

When this final output in the accumulator exceeds certain threshold value which has been set up in advance, the product is considered to have expired.

4. Simulation Results

In order to verify the operation of the proposed freshness emulator, extensive simulations were carried out using the 6M1P 0.18 μm TSMC (Taiwan Semiconductor Manufacturing Corporation) CMOS process technology parameters. The Tanner T-SPICE v.12 circuit-level simulation software was used for this purpose. A 3 V supply voltage was used for the design. Bias voltages of 2.2 V and 2.4 V are applied to the base of NPN1 and NPN2 respectively corresponding to a base activation energy of 0.2 eV. With the squaring circuit this corresponds to an equivalent of activation energy of 0.4 eV. Fig. 4 shows the output current of the trans-linear divider for temperatures of -50 °C, -30 °C, -10 °C, 0 °C, 20 °C, 30 °C, 40 °C, 50 °C and 70 °C respectively varying between 0.7 mA to 1.7 mA. These currents are squared by the squaring circuit and mirrored to the ring oscillator for bias current control for all the 5 stages. The relationship between temperature and the output current is somewhat non-linear in accordance with equations (6) and (7), and, as can be seen from the plot in Fig. 4. However, the monotonic relationship between temperature and bias current ensures the validity of the sensory emulation proposed by this circuit.

Next, Fig. 5 shows the time-period of oscillations for three different temperatures, being 6.36 ns at 70 °C, 6.9 ns at 50 °C and 7.3 ns at 40 °C. The time-period of oscillation is proportional to the rise-time and fall-time of the oscillation pulses. Higher sourcing and sinking currents provided by the bias control of the oscillator stages at higher temperatures results in shorter time-periods. So, for the same time interval Δt (e.g. 0.1 s) the counter will provide a count of 15723270 pulses at 70 °C, 14492753 pulses at 50 °C and 13698630 pulses at 40 °C. A 32-bit up-counter is thus used in Fig. 3 for counting the pulses during a short period of 0.1 sec. Count accumulated by the adder-accumulator would be considerably higher for exposure to long periods of higher temperatures during transport and distribution, compared to exposure to lower temperatures. When the contents of the accumulator are compared with a preset count the expiry status is determined for the product/perishables. The power dissipated by the sensor was mostly due to the dc bias currents in the analog front-end circuit. The digital back-end block being designed using static CMOS logic gates only dissipates power during logic transition (dynamic power dissipation), and, its static power dissipation is almost zero. The sensor circuit was found to have an overall dc power drain of around 16 mW.

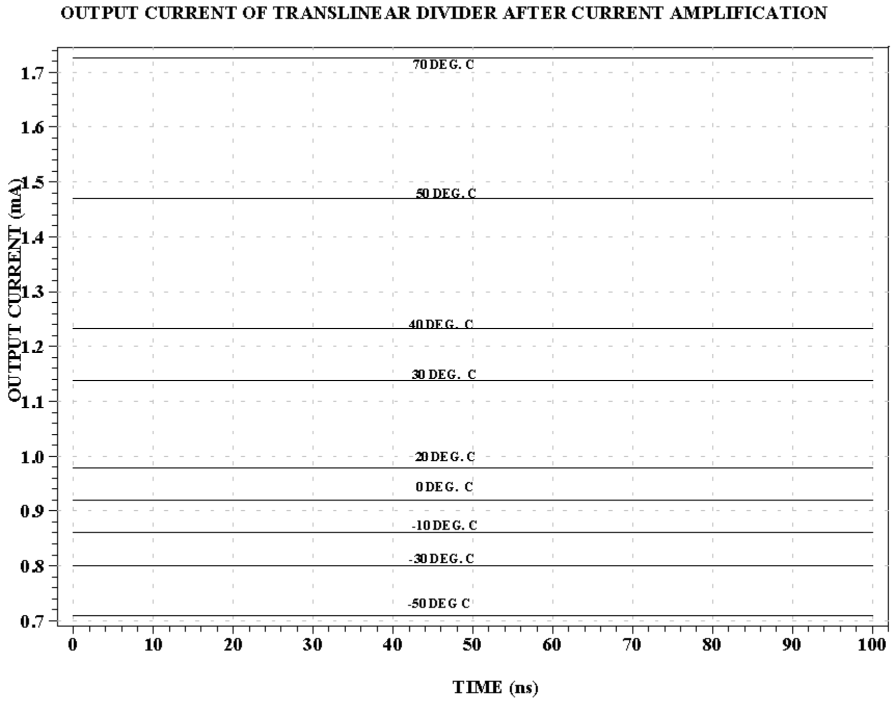

Fig. 4. Output currents of the trans-linear divider for temperatures of -50 °C, -30 °C, -10 °C, 0 °C, 20 °C, 30 °C, 40 °C, 50 °C and 70 °C respectively.

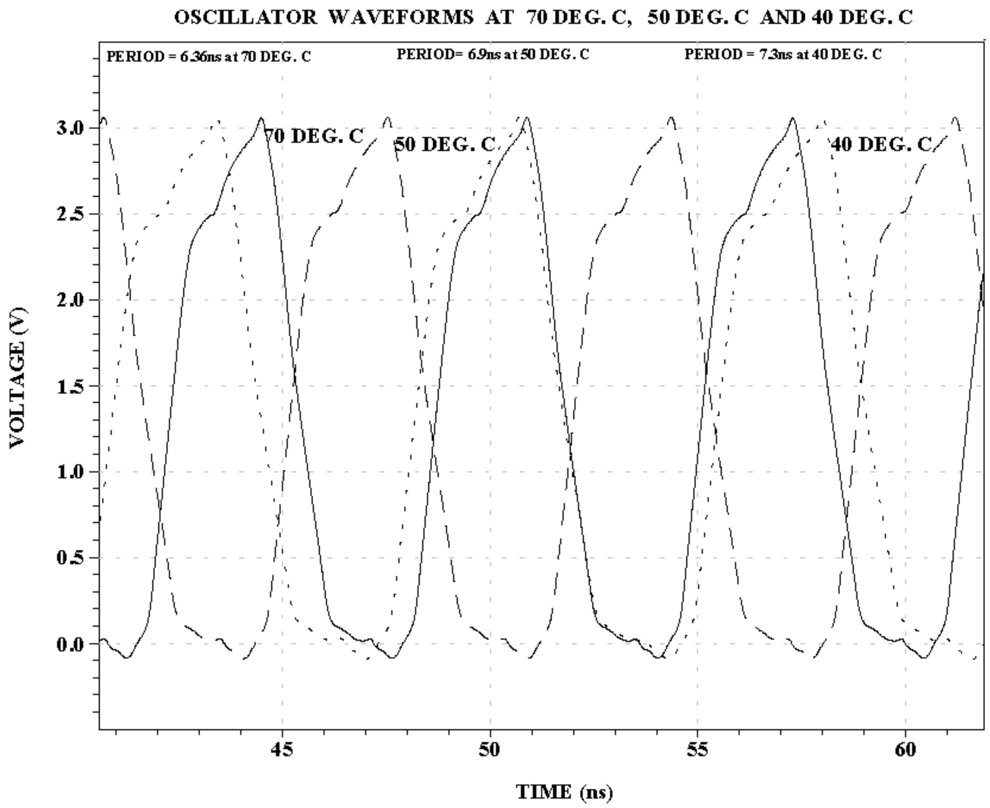

Fig. 5. Oscillator waveforms for the current controlled ring oscillator showing time periods of 6.36 ns, 6.9 ns and 7.3 ns respectively for temperatures of 70 °C, 50 °C and 40 °C respectively.

5. Conclusion

An emulating sensor for monitoring the quality of perishables, using MOSFET devices in the strong inversion region of operation along with parasitic PNP thermo-sensors is proposed. The circuit is implemented using a standard low-cost CMOS process technology. The circuit provides higher dynamic range in terms of activation energy from 0.1 V to 0.8 V using the PNP thermo-sensors and CMOS squaring circuit. Furthermore, the design requires less hardware than the circuit proposed by [1], [2]. Simulations indicate that the topology is quite sound and provides sufficient resolution and thermal dynamic range to be implemented in monitoring food freshness. The sensor can thus be used for monitoring the freshness of perishables over long periods of transportation, distribution, storage and shelf-life.

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