P-143: A Novel Current-Scaling a-Si:H TFTs Pixel Electrode Circuit for Active-Matrix Organic Light-Emitting Displays

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Abstract

Hydrogenated amorphous silicon thin-film transistor (a-Si:H TFT) pixel electrode circuit with a function of current scaling is proposed for active-matrix organic light-emitting displays (AM-OLEDs). In contrast to the conventional current mirror pixel electrode circuit, in this circuit a high data-to-organic light-emitting device (OLED) current ratio can be achieved, without increasing the a-Si:H TFT size, by using a cascade structure of storage capacitors. Moreover, the proposed circuit can compensate for the variations of TFT threshold voltage. Simulation results, based on a-Si:H TFT and OLED experimental data, showed that a data-to-OLED current ratio larger than 10 and a fast pixel programming time can be accomplished with the proposed circuit.

I. Introduction

Since the first observations of the light emission in small molecules based organic light-emitting diodes (OLEDs) [1], there is increasing interest in their applications to the large area flat panel displays due to their adequate opto-electric properties, versatility of colors, large viewing angle and potential low fabrication cost [2]-[4]. Recently it was also demonstrated that a combination of the OLEDs with the amorphous silicon thin-film transistor (a-Si:H TFT) active-matrix (AM) arrays can be used for high-resolution active-matrix OLEDs [5]-[10]. Due to non-negligible TFT characteristic variations (threshold voltage and field-effect mobility shifts), current driving schemes with four-TFT pixel electrode circuits have been proposed as a useful approach to drive AM-OLED, whereby the current signal provided by external driver modulates directly the pixel electrode circuits [9][10]. The four-TFT circuits can not only provide a continuous excitation to OLED, but at the same time it can also compensate for the TFT threshold voltage variation.

Although the current driving scheme improves the display luminance uniformity, a large timing delay observed at a low data current is due to combination of a high OLED efficiency and a large interconnect parasitic capacitances that must be charged. To reduce the programming time delay, the pixel electrode circuits based on an adjustable TFTs geometric ratio with the current scaling function have been proposed [11][12]. In these circuits a high data-to-OLED-current ratio can only be achieved for a large geometric ratio of T4 to T3. This can limit the pixel electrode aperture ratio.

In this paper we present an improved current driven pixel circuit based on a-Si:H TFT technology with the current scaling function. A cascade structure of storage capacitors approach was used in this work to achieve a high data-to-OLED-current ratio without increasing TFTs siz. The proposed pixel electrode circuit can also compensate for a-Si:H TFT threshold voltage variation so that uniform display luminance can be expected

II. Proposed pixel electrode circuit

The proposed current driven pixel electrode circuit consists of three switching TFTs (T1, T2, T4), one driving TFT (T3) and two storage capacitors (C_{ST1}, C_{ST2}) connected between a scan line and ground with a cascade structure, as shown in Fig. 1. The operation of the circuit is controlled by four external terminals: V_{SCAN}, V_{CTRL}, I_{DATA} and ground. The signals of V_{SCAN}, V_{CTRL}, and I_{DATA} are supplied by external drivers while the cathode of OLED is grounded. The operation of this pixel electrode circuit can be described as follow.

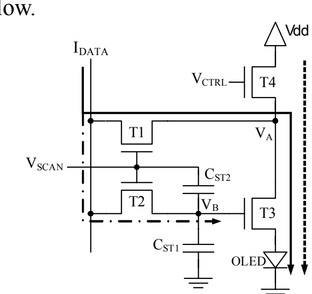

Fig. 1. Schematic diagram of current driven pixel circuit with cascade structure of storage capacitors.

During the ON-state, the scan line signal V_{SCAN} turns on the switching transistors T1 and T2. During this time, a data current signal I_{DATA} passes through T1 and T3 to OLED, shown as the solid line in Fig. 1, and sets the voltage at the T3 drain electrode (nodes A). At the same time the voltage at the T3 gate electrode (node B) is set by I_{DATA} passing through T2 (dash line). The control signal V_{CTRL} turns T4 off to ensure that no current flows through T4. Consequently, in ideal case the OLED current in ON-state, $I_{OLED-ON}$, should be equivalent to I_{DATA}. Since the T3 drain and gate electrodes are at the same potential, T3 will operate in the deep saturation region, e.g., $V_{DS} > V_{GS}-V_{TH}$ (threshold voltage) and the V_A and V_B voltages at both nodes are determined automatically. If T3 threshold voltage changes and if this change is not higher than V_{SCAN} amplitude, the T3 gate voltage, V_{B-ON}, will be adjusted accordingly to ensure the identical I_{DATA} in ON-state. Therefore, V_{B-ON} is always adjusted to keep I_{DATA} at about the same value regardless of a-Si:H TFT threshold voltage. The V_{B-ON} will also be stored in both C_{ST1} and C_{ST2} and the voltage across C_{ST2} is $V_{SCAN}-V_{B-ON}$.

When the pixel changes from ON- to OFF-state, V_{SCAN} turns off T1 and T2 and V_{CTRL} simultaneously turns on T4. Because C_{ST2} is connected between the scan line and the node B to form a cascade structure with C_{ST1}, V_{SCAN} change from high to ground state will reduce V_{B-ON} to V_{B-OFF} due to the feed-through effect of the capacitors. V_{B-OFF} can be derived from the charge conversation theory, and is given by Eq. (1), in which ΔV_{SCAN} is an amplitude of V_{SCAN} (=$V_{SCAN-ON} - V_{SCAN-OFF}$).

$$V_{B-OFF} = V_{B-ON} - \Delta V_{SCAN} \cdot \frac{C_{ST2}}{C_{ST1} + C_{ST2}} \qquad \text{Eq. (1)}$$

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A reduced T3 gate voltage, $V_{B\text{-}OFF}$, will be hold in C_{ST1} and C_{ST2} and it continuously will turn on T3 during this time period. Since T4 works as a switch so that the T4 turn-on resistance is insensitive to TFT threshold voltage shift. The T3 drain is connected to Vdd to ensure that T3 is operating in the deep saturation region. A current smaller than I_{DATA} , shown as the dash line in Fig. 1, will be generated by $V_{B\text{-}OFF}$ and will pass through T4 and T3 to OLED. Consequently, the OLED current in OFF-state, $I_{OLED\text{-}OFF,}$ will be smaller than I_{DATA}.

Since the T3 gate voltage decreases from $V_{B\text{-}ON}$ to $V_{B\text{-}OFF}$, the OLED driving current is scale-down from ON- to OFF-state by the storage capacitor cascade structure. The quantity of voltage drop, shown as $\Delta V_{SCAN} \cdot C_{ST2}/(C_{ST1}+C_{ST2})$ in Eq. (1), will increase with increasing ΔV_{SCAN} and C_{ST2} value and will lead to a smaller $I_{OLED\text{-}OFF}$. In other words, the scale-down ratio, $R_{SCALE}=I_{OLED\text{-}ON}/I_{OLED\text{-}OFF}$, is related to both the size of C_{ST2} and to ΔV_{SCAN}. Therefore it is expected that a larger C_{ST2} will result in larger R_{SCALE}. Consequently, when a very large data current I_{DATA} is used to charge the pixel electrode and to shorten the pixel programming time, at the same time a smaller driving current $I_{OLED\text{-}OFF}$ can be achieved for lower gray scales.

III. Parameter extraction and pixel electrode circuit design

Synopsis H-SPICE simulation tool with the Rensselaer Polytechnic Institute (RPI) Troy, NY, a-Si:H TFT model [13][14] was used to evaluate the proposed pixel electrode circuit. The a-Si:H TFT parameters developed within our group were used in this simulation [15]. To simulate the behavior of OLED the conventional semiconductor diode model, with the parameters extracted for organic polymer light-emitting device (PLED) fabricated in our laboratory, was used. In the pixel design, a C_{ST1} with the fixed size of 2.5 pF was used and C_{ST2} size was varied from 210 to 625 fF to achieve different C_{ST2}/C_{ST1} ratios. Since T2 works as a switch in this circuit, its size can be smaller in comparison with other TFTs. The a-Si:H TFT parameters used for this pixel electrode circuit simulation are given in Table 1.

Table 1. The parameters used in pixel circuit simulation.

Device parameters for TFT	
W/L (T_1, T_3, T_4) (μm)	150/6
W/L (T_2) (μm)	50/6
V_{TH} (V)	2
μ_{FE} (cm^2/V-sec)	1.9
I_{OFF} (pA)	0.1
C_{ST1} (pF)	2.5
C_{ST2} (fF)	210~625
Device parameters for OLED	
n	31
R_S (Ω)	20
I_S (A)	8 x 10^{-5}
C_{OLED} (pF)	3
Supplied signals	
V_{SCAN} (V)	0~35
V_{CTRL} (V)	0~35
Vdd (V)	35
I_{DATA} (μA)	0~5
Times (mSec)	
t_{ON}	0.33
t_{OFF}	33

IV. Simulation results and discussion

The proposed current-scaling pixel electrode circuit was evaluated using H-SPICE and an example of the waveforms is shown in Fig. 2. In this specific case, in ON-state, the voltages at node A and B are set to appropriate levels to allow I_{DATA} of 4 μA to pass through T3. It should be noticed that in ideal case the voltages at A and B nodes are identical. However, in practice, there will be a difference between A and B voltages because I_{DATA} passing through T1 causes a voltage drop between drain and source electrodes of T1. In OFF-state, the T3 gate voltage decreases from 13.3 ($V_{B\text{-}ON}$) to 9.2 V ($V_{B\text{-}OFF}$) and V_A changes from 12.3 to 28.1 V. V_A higher than V_B keeps T3 operating in deep saturation region and the drop of V_B results in the decrease of I_{OLED} from 4 (= $I_{OLED\text{-}ON}$) to 1.4 μA (= $I_{ONED\text{-}OFF}$). From this figure it is clear that $I_{OLED\text{-}ON}$ is different from $I_{OLED\text{-}OFF}$. The $I_{OLED\text{-}ON}/I_{OLED\text{-}OFF}=R_{SCALE}$ (4/1.4=2.86) is obtained in the proposed circuit.

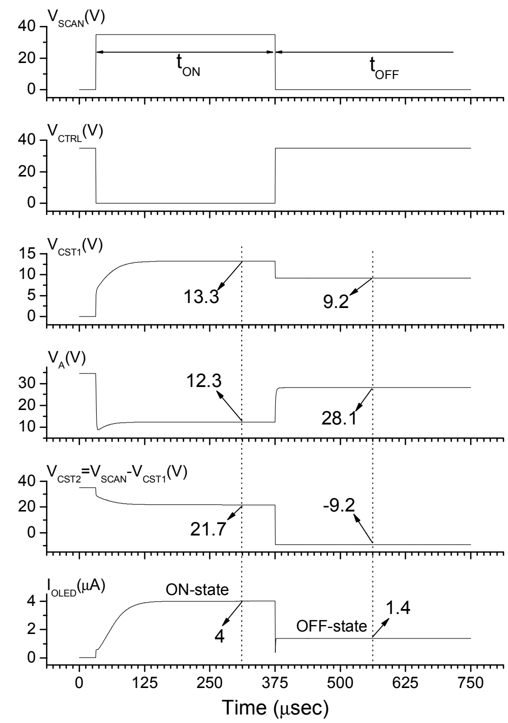

Fig. 2. An example of pixel operation waveforms simulated by H-SPICE for Vdd=35 V.

Since $I_{OLED\text{-}ON}$ ($=I_{DATA}$) is larger than $I_{OLED\text{-}OFF}$ by a factor of R_{SCALE}, the average OLED current (I_{AVG}) for the pixel electrode circuit should be properly defined:

$$I_{AVG} = \frac{I_{OLED-ON} \cdot t_{ON} + I_{OLED-OFF} \cdot t_{OFF}}{t_{ON} + t_{OFF}} \qquad \text{Eq. (2)}$$

Where t_{ON} and t_{OFF} denote the select and deselect periods during the frame time, respectively. Since the $I_{OLED\text{-}ON} = I_{OLED\text{-}OFF} \cdot R_{SCALE}$, Eq. (2) can be written as:

$$I_{AVG} = I_{OLED-OFF} \cdot \left[\frac{R_{SCALE} \cdot t_{ON} + t_{OFF}}{t_{ON} + t_{OFF}} \right] \qquad \text{Eq. (3)}$$

From this equation an accurate I_{AVG} can be calculated for various combinations of $I_{OLED\text{-}OFF}$ and R_{SCALE} to satisfy the display requirements for different gray scales. As it will be shown below to display low gray scales, not only a low $I_{OLED\text{-}OFF}$ but also a high $I_{OLED\text{-}ON}$ are needed at the same time to control both a low display luminance and a fast programming time. Combination of a low $I_{OLED\text{-}OFF}$ and a large R_{SCALE} can be used to satisfy this display requirement. For higher gray scales, a high $I_{OLED\text{-}ON}$ is not needed since a high $I_{OLED\text{-}OFF}$ can be achieved. Therefore, a combination of a large $I_{OLED\text{-}OFF}$ and a low R_{SCALE} is appropriate to display high gray scales.

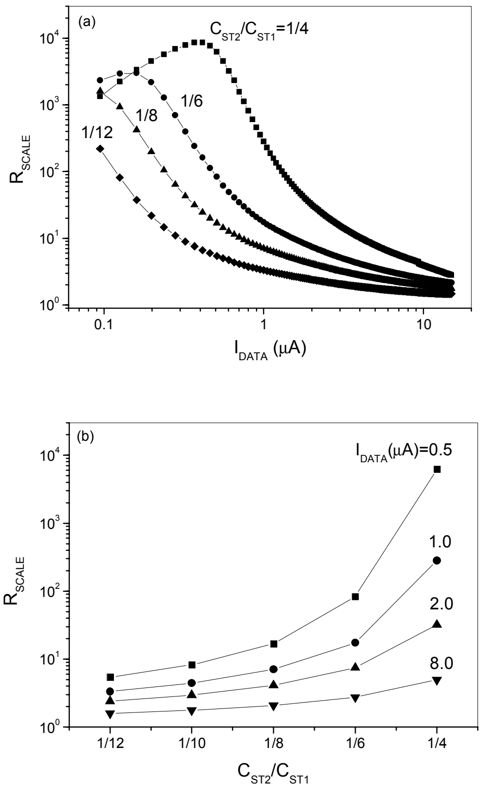

Fig. 3. Variation of the current scaling ratio versus (a) data current and (b) ratio of storage capacitances.

Since the scale-down ratio (R_{SCALE}=$I_{OLED\text{-}ON}$/$I_{OLED\text{-}OFF}$), will affect the capability of the proposed pixel electrode circuit, it is important to evaluate its evolution with the I_{DATA} (=$I_{OLED\text{-}ON}$) and C_{ST2}/C_{ST1}. The variation of R_{SCALE} as a function of I_{DATA} is shown in Fig. 3(a). From this figure we can see that when C_{ST2}/C_{ST1}=1/12, R_{SCALE} decreases from 210 to 1.5 as I_{DATA} increases from 0.1 to 10 μA. In this specific case since $V_{B\text{-}ON}$ at high gray scale is larger than that at low gray scale, it is expected that a large I_{DATA} will pass through T3. And a fixed voltage drop induced by $\Delta V_{SCAN} \cdot C_{ST2}/(C_{ST1}+C_{ST2})$ is relatively small in comparison to $V_{B\text{-}ON}$, hence data current drop is expected to be small. In the other words, a fixed voltage drop can dramatically affect $V_{B\text{-}ON}$ at low gray scales where $V_{B\text{-}ON}$ is small. Therefore, desirable a high R_{SCALE} at low gray scales and a low R_{SCALE} at high gray scales can be achieved by proposed pixel electrode circuit. The variation of R_{SCALE} with the C_{ST2}/C_{ST1} is as shown in Fig. 3(b); this figure was calculated from Fig. 3(a). It should be mentioned that, Eq. (1), a large C_{ST2}/C_{ST1} ratio can induce a large V_B offset between pixel ON- and OFF-state. Consequently, V_B decrease will result in the scale-down of the data current and in a high R_{SCALE}. The simulation results showed that when I_{DATA} is fixed, R_{SCALE} increases when C_{ST2} increases from 210 to 625 fF, corresponding to an increase of C_{ST2}/C_{ST1} from 1/12 to 1/4. Fig. 3(b) also demonstrates that when a smaller I_{DATA} is used, a higher R_{SCALE} can be achieved with the constant C_{ST2}/C_{ST1}.

The current-scaling function is performed so that the large programming current can be reduced to an appropriate value when the pixel operates from the ON- to the OFF-state. In ON-state, the $I_{OLED\text{-}ON}$ (=I_{DATA}) are identical in not only the conventional but also the proposed pixel electrode circuits because the external driver directly controls the current, Fig. 4(a). When pixels work in OFF-state, the proposed pixel circuit reveals an advantageous current-scaling ability in comparison with the conventional current-driven pixel electrode circuit which just ideally keeps the $I_{OLED\text{-}OFF}$ equivalent to $I_{OLED\text{-}ON}$, Fig. 4(b).

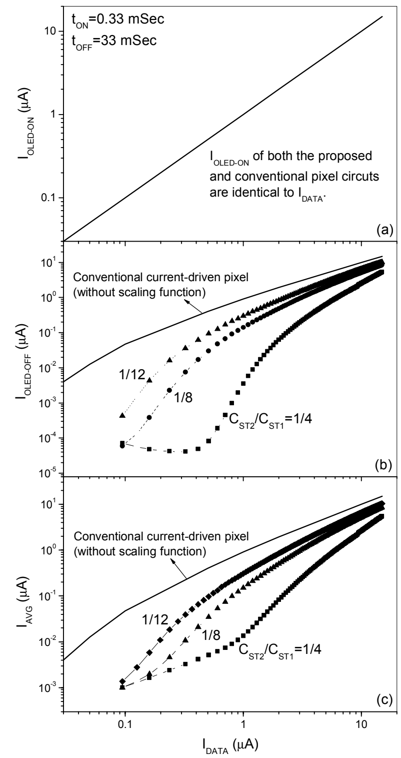

Fig. 4. Variation of the $I_{OLED\text{-}ON}$, $I_{OLED\text{-}OFF}$ and I_{AVG} during one frame period versus I_{DATA} (=$I_{OLED\text{-}ON}$) at various C_{ST2}/C_{ST1} ratio.

From Fig. 4(b), it is obvious that the large C_{ST2}/C_{ST1} results in the significant decrease of $I_{OLED\text{-}OFF}$. Moreover, since the OFF-state period is much longer than ON-state, the small $I_{OLED\text{-}OFF}$ in OFF-state can further reduce the I_{AVG} even if the $I_{OLED\text{-}ON}$ is large. According to Eq. (3), the plots of I_{AVG} versus I_{DATA} (=$I_{OLED\text{-}ON}$) in one frame period (t_{ON} + t_{OFF}) with C_{ST2}/C_{ST1} ratios as a parameter are shown in Fig. 4(c). From these figures, it is evident that I_{DATA} larger than I_{AVG} can be used to program the proposed pixel in ON-state without increasing the a-Si:H TFTs geometric size. Hence using an additional C_{ST2} to form a cascade capacitors structure, a large R_{SCALE} can be achieved and a high I_{DATA} can accelerate the pixel programming in ON-state.

To demonstrate the proposed pixel electrode circuit outstanding current scaling function in comparison with both the conventional current-driven and current-mirror pixels, one simulated I_{AVG} as a function of I_{DATA} for each pixel electrode circuit was shown in Fig. 5. Although the current–mirror pixel is able to scale down I_{DATA}, the scale-down ratio R_{SCALE} is constant in the whole range of I_{DATA}. In current-mirror pixel, a large I_{DATA} for high gray scales will result in a high power consumption due to the fixed scale-down ratio. In addition, to achieve the current scaling function, a larger driving TFT T4 needed in current-mirror pixel will substantially reduce the pixel electrode aperture ratio. From Fig. 5, we can conclude that with the I_{DATA} ranging from 0.1 to 10 μA, our proposed pixel circuit can achieve I_{AVG} ranging from 1 nA to 5 μA, which represents much wide range in comparison with the conventional current-driven pixel (0.05 to 10 μA) and the current-mirror pixel (0.01 to 2.5 μA). Therefore, the proposed pixel circuit can yield not only a high I_{DATA} and a high R_{SCALE} for the low gray scales, but also reasonable I_{DATA} for a high gray scale to avoid large display power consumption.

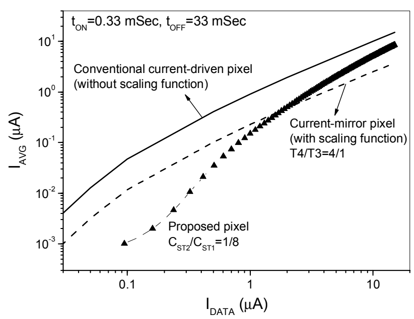

Fig. 5. Comparison of I_{AVG} as a function of I_{DATA} among conventional current-driven, current-mirror, and proposed pixels.

To investigate the influence of T3 V_{TH} variation on pixel circuit performance, various threshold voltage deviations ($\Delta V_{TH}=V_{TH}$(after stress)-V_{TH}(initial)), based on the experimental results, have been used in circuit simulation. The variation of $\Delta I_{OLED\text{-}OFF}$ as a function of ΔV_{TH} is shown in Fig. 6(a). From this figure we can conclude that $\Delta I_{OLED\text{-}OFF}$ is lower than 3 % when $I_{OLED\text{-}OFF}$ is higher than 1.0 μA even if ΔV_{TH}=4 V. However, $\Delta I_{OLED\text{-}OFF}$ substantially increases when $I_{OLED\text{-}OFF}$ is lower than 100 nA. This is due to the influence of charge injection of switching T2 on $V_{B\text{-}ON}$. Since a small $V_{B\text{-}ON}$ will result from a low driving current $I_{OLED\text{-}ON}$ at low gray scales, the charge carrier released from T2, when T2 is turn-off, can reduce the $V_{B\text{-}ON}$. Therefore, $V_{B\text{-}ON}$ can be modified by not only a voltage drop induced by cascade structure of C_{ST1} and C_{ST2} but also by a charge injection from T2. In addition, the V_{TH} shift of all TFTs can lead to a higher sensitivity of $V_{B\text{-}ON}$ to the charge injection from T2. Therefore, large storage capacitor is needed to eliminate the effect of T2 charge injection. As shown in Fig. 6(b), when large C_{ST2}/C_{ST1} is used, a significant reduction of $\Delta I_{OLED\text{-}OFF}$ at low gray scales is observed in comparison to C_{ST2}/C_{ST1}=0. From our data shown in Figs. 3(b) and 6(b), we can conclude that a large C_{ST2}/C_{ST1} can achieve a high R_{SCALE} as well as a small $\Delta I_{OLED\text{-}OFF}$.

V. Conclusion

In conclusion, we proposed a pixel electrode circuit based on a-Si:H TFT technology and current driving scheme. We have shown that this circuit can achieve a high current scale-down ratio by a cascade structure of storage capacitors instead of increasing TFT size. In the proposed circuit, the ON-state data current 10 times larger than OLED current in OFF-state can be achieved to accelerate the pixel programming time. Furthermore, the threshold voltage variation of all TFT can also be compensated by proposed circuit. Consequently, this new pixel electrode circuit has great potential for large size, high-resolution a-Si:H TFT AM-OLEDs.

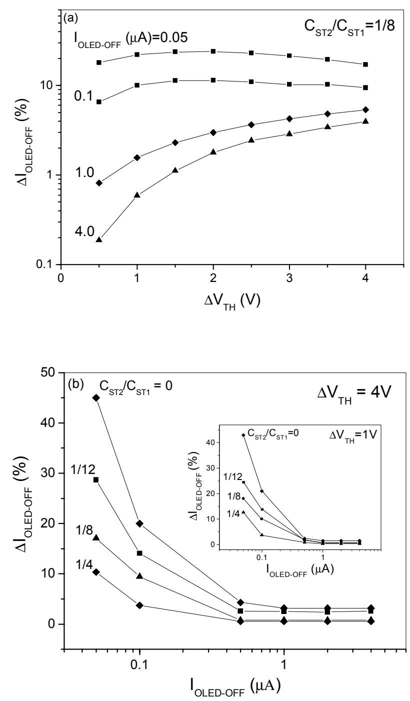

Fig. 6. (a)Variation of $\Delta I_{OLED\text{-}OFF}$ as function of TFT threshold voltage shift. (b) $\Delta I_{OLED\text{-}OFF}$ versus OLED current during display operation OFF-state for different C_{ST2}/C_{ST1} and ΔV_{TH}=4V. The data for ΔV_{TH}=1V is shown in insert.

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