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(54) Titre : PANNEAUX ARRIERE D'ECRAN AMOLED - CIRCUITS DE COMMANDE DES PIXELS, ARCHITECTURE DE RESEAU ET COMPENSATION EXTERNE

(54) Title: AMOLED DISPLAY BACKPLANES - PIXEL DRIVER CIRCUITS, ARRAY ARCHITECTURE, AND EXTERNAL COMPENSATION

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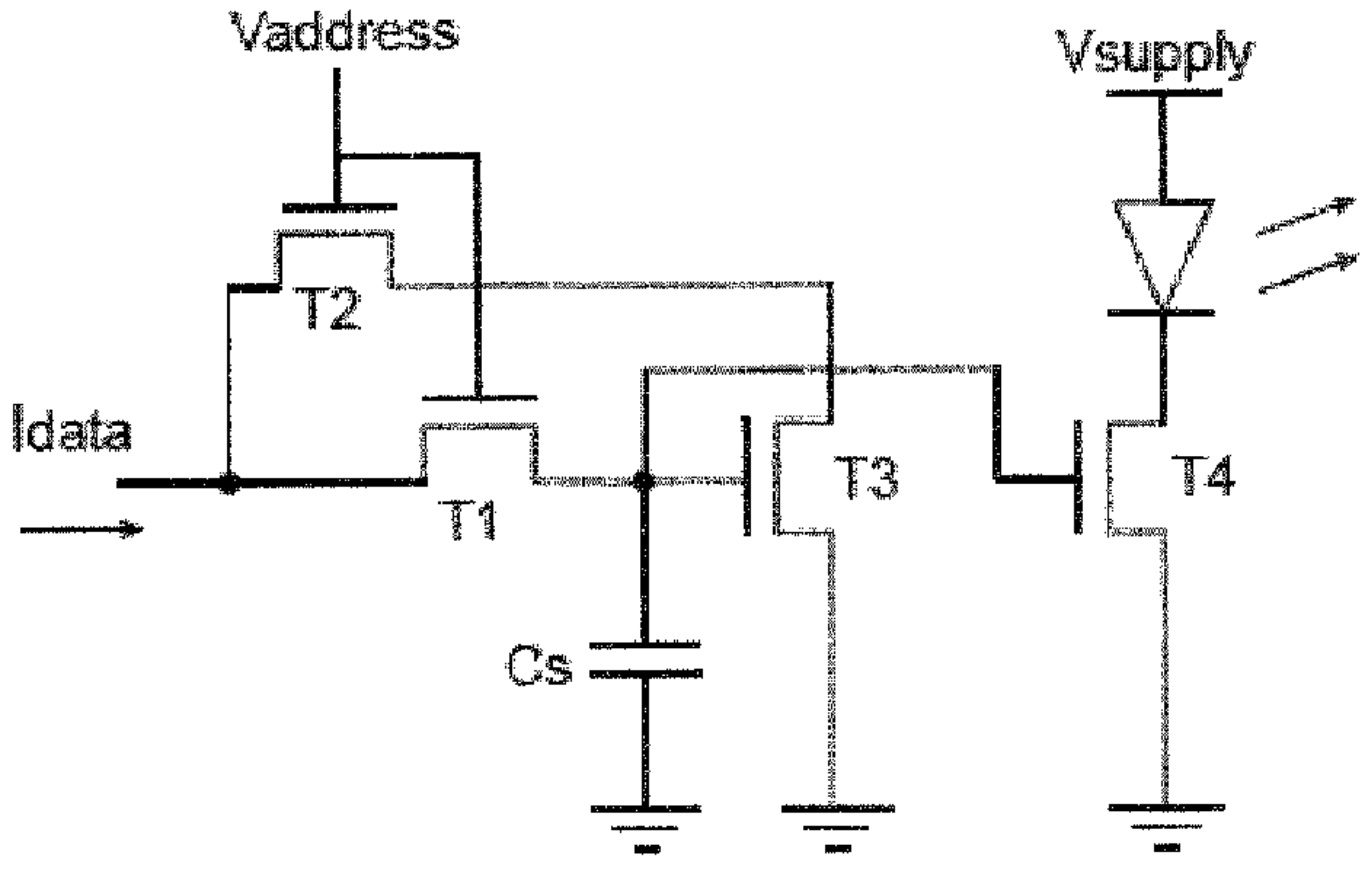

4-TFT current-programmed pixel

(57) Abrégé/Abstract:

Pixel circuits, array architecture, and external compensation scheme for AMOLED displays are provided. The pixel circuits are current programmed, drive an organic light emitting diode (OLED) with the desired current, and compensate for increase in the threshold voltage of the drive TFT. The new array architecture presented allows the use of current sinks to drive current

(57) **Abrégé(suite)/Abstract(continued):**
programmed pixels. The external compensation scheme uses feedback with circuitry that is external to the display array, to monitor changes in the OLED current and adjust the input of the pixel circuit accordingly.

Abstract

Pixel circuits, array architecture, and external compensation scheme for AMOLED displays are provided. The pixel circuits are current programmed, drive an organic light emitting diode (OLED) with the desired current, and compensate for increase in the threshold voltage of the drive TFT. The new array architecture presented allows the use of current sinks to drive current programmed pixels. The external compensation scheme uses feedback with circuitry that is external to the display array, to monitor changes in the OLED current and adjust the input of the pixel circuit accordingly.

AMOLED display backplanes – Pixel Driver Circuits, Array Architecture, and External Compensation
(Description of the Invention)

Field of the Invention

The present invention relates to active matrix organic light emitting diode (AMOLED) displays, more specifically to a pixel circuits, active matrix array architecture, and the enhancement of OLED current stability by using external feedback and compensation.

Background of the Invention

Amorphous silicon thin film transistors (a-Si:H TFT) are suitable for active matrix organic light emitting diode (AMOLED) display backplanes due to their low leakage, good spatial uniformity, and the possibility of a low temperature process. A 2-TFT voltage driven circuit is the simplest and smallest AMOLED pixel circuit. However, with this circuit, the OLED drive current drops over time due to threshold voltage shifts in the drive TFT. The nature of threshold voltage increase is shown in Figure 1. Due to this instability, better circuits are required to compensate for the decay in current through the OLED.

Current Programmed Circuits

A self-compensating 4-TFT current programmed circuit is developed to overcome time dependent threshold voltage shifts described above and keep the OLED drive current constant. Figure 2 shows the 4-TFT current-programmed pixel circuit 10, which has been previously patented by Ignis Innovation Inc.

It is desirable to provide new pixel circuits, array architectures, and external feedback and compensation schemes for AMOLED displays which meet the following specifications:

- Perfect functionality – **100% threshold voltage shift compensation** – independence from external parameters like temperature, ambient lighting etc.
- **High Lifetime** – in excess of 10000hrs and **stability** for large range of operation
- **Quick programming** < 70μs
- **Low layout area**
- **Low power consumption**

Summary of the Invention

It is an object of the invention to provide novel current programmed ΔV_T compensating pixel circuits, a new backplane architecture that is amenable to current programmed pixel circuits, a method for accurately determining OLED current by using external feedback and compensation, and a system that obviates or mitigates at least one of the disadvantages of existing systems.

In accordance with an aspect of the present invention, there is provided a backplane comprised of pixel circuits, active matrix array, and external feedback mechanisms.

Other aspects and features of the present invention will be readily apparent to those skilled in the art from a review of the following detailed description of preferred embodiments in conjunction with the accompanying drawings.

Brief Description of the Drawings

The invention will be further understood from the following description with reference to the drawings in which:

Figure 1 is the threshold Voltage shift vs. Stress Voltage of a discrete a-Si TFT

Figure 2 is a 4-TFT current-programmed pixel

Figure 3 is a 3-T current programmed Vt-shift compensating AMOLED pixel circuit

Figure 4 is a 4-T split OLED current programmed Vt-shift compensating AMOLED pixel circuit

Figure 5 is a 4-T split OLED current programmed Vt-shift compensating AMOLED pixel circuit

Figure 6 is a 5-T current programmed Vt-shift compensating AMOLED pixel circuit with redundancy

Figure 7 is a new array architecture using current sources and current sinks to drive current programmed pixels

Figure 8 is a schematic of a current sink using n-channel TFTs

Figure 9 is a schematic of 3-TFT pixel driver circuit with special addressing

Figure 10 is the new array architecture implemented with the 3-TFT current programmed pixel circuit

Figure 11 is a schematic of a current feedback pixel circuit with the external control system driving the circuit

Figure 12 is a schematic of current feedback pixel and an opamp as the external control unit

Figure 13 is a schematic of pixel circuits of Figure 11 in the same column as the external driving opamp, reference current source, and reference resistor

Figure 14 is a simulation waveforms of row select and output current of the pixel of Figure 11

Figure 15 is a current feedback pixel circuit with dummy transistor connected to the gate of drive TFT

Figure 16 is a simulation waveforms of the output current of the circuit of Figure 15 with and without the dummy transistor

Figure 17 is a schematic of a current feedback pixel circuit with OLED connected to the source of the drive TFT

Figure 18 is a simulation waveforms of the circuit of Figure 17

Figure 19 is a schematic of current feedback pixel circuit with its feedback resistor connected to the drain of the n-channel driving TFT and a p-channel feedback TFT switch

Figure 20 is a schematic of current feedback pixel circuit with its feedback resistor connected to the source of the p-channel driving TFT and a p-channel feedback TFT switch

Detailed Description of the Preferred Embodiment(s)

Pixel Circuits

Pixel circuits of the present invention are used in amorphous and poly silicon-based active matrix OLED Displays that are current or voltage programmed. This design:

- Compensates for the Threshold-Voltage shift in amorphous silicon thin-film transistors;
- Offers sufficient characteristics to drive an OLED pixel;
- Is able to be fabricated and integrated into an array;
- Presents an array architecture where current sinks can be used instead of current sources to program the pixels;

- Shows a method to implement on-panel current sinks in a-Si:H or poly-Si:H, where the current sinks can be voltage or current controlled; and
- Demonstrates the use of external compensation through feedback to ensure that the OLED drive current stays constant.

Figure 3 shows a 3-TFT current programmed Vt shift compensating pixel circuit that uses the OLED I-V characteristic in the reverse bias regime during programming, and in the forward bias regime during operation. The compensation occurs due to the feedback provided by T1, wherein the capacitor Cs is charged up to a voltage that allows all of Idata to pass through T3. The benefit of this circuit is reduced size and better OLED current stability.

In the 4-TFT circuit of Figure 2, the current mirror is not completely balanced since the drain voltages of T3 and T4 are not equal or similar. The current programmed split-OLED Vt shift compensating circuit shown in Figure 4 eliminates this problem by using two OLEDs, one connected to the drain of T3 and one to the drain of T4. The ratio of the OLED areas is equal to the ratio of the (W/L) of T4 and T3.

Figure 5 shows a 4-TFT current programmed Vt shift compensating circuit that works with the OLED connected to the source terminal of the TFTs T3 and T4. This provides excellent OLED current stability when used with a non-inverted OLED structure.

Figure 6 shows a 3-TFT AMOLED pixel circuit and its related voltage and current waveforms. It consists of three n-type TFT transistors, one capacitor and one OLED. The pixel circuit also has two row controlling signals (Vc and Vsel), one data column signal (Idata) and one power supply connection. The pixel circuit has two operating modes, writing mode and hold mode. During writing mode, Vsel and Vc signals are high. As a result and T3 and T2 TFTs turn on and the data current goes through T1 and gate-source voltage of T1 is saved in Cs capacitor. It should be considered that no current goes through OLED during writing mode because it is in reverse bias. In hold mode Vsel is low so T2 and T3 turn off. Cs capacitor holds its voltage so that the gate-source voltage of T1 has the same voltage that it had during writing mode. As a result, T1 current value remains unchanged. As Vc is low, T1 current goes through OLED during writing mode.

In all the pixel circuits presented in published literature, the TFT driving the OLED current is always in the ON state. This causes the Vt of that TFT to increase rapidly. In Figure 7, we present a 5-TFT redundant current programmed Vt shift compensating pixel circuit that consists of two drive TFTs, each running at a 50% duty cycle. This allows for a much slower rate of Vt shift. During programming, V-sel and Sel-1 can be ON (enabling drive TFT T3), or V-sel and Sel-2 is ON (enabling drive TFT T5) alternatingly. The Vt can also be reduced when either drive TFT is OFF by applying a negative voltage or negative current.

The in-pixel redundancy concept is new in AMOLED displays, and can be applied to any regular non-redundant pixel circuit. Moreover, the concept can be extended to more than two drive TFTs, resulting in a further reduction in duty cycle, and hence a reduction in Vt shift. The disadvantage of redundancy is increased pixel area, which is not a limitation in a state-of-the-art process because of scaling considerations.

New Array Architecture

In the conventional array architecture, the image data (provided in the form of a voltage or current) is fed to the pixel circuit. However, in the case of current programmed arrays, this means that current sources are required.

We present an alternative method for driving current programmed arrays. The idea is to use a constant current source coupled with a variable current sink connected in a 'T-junction' topology. The third terminal of the junction goes to the input of the pixel circuit. The setup works in accordance with Kirchoff's current law, such that the difference between the current provided by the current source, and that absorbed by the current sink, goes to the pixel circuit. Thus current sinks can be used to program the pixel circuits in current programmed arrays.

The constant current source and/or the variable current sink can be implemented on the display array itself. The current sink can be controlled by an analog voltage, which means that conventional LCD drivers can be used to drive a current programmed array.

A specific example of this invention using amorphous silicon technology in AMOLED displays is shown in Figure 8.

The display uses an external constant current source per column, and an on-board variable current sink per column. LCD voltage source drivers may be used for controlling the variable current sink.

An example of a current sink using n-channel TFTs is given in Figure 9. Here, T1 is operated in linear mode and should be made very large to give sizable current. In addition, if it is large enough gate bias may be decreased to give less Vt shift.

A 3-T pixel driver with special addressing to have reliable current programming is shown in Figure 10. Here:

- During the write period, the rise in SEL2 (of each column) turns off the OLED. Thus, the programming is done without any error.
- During the drive period, SEL2 returns to zero, turning the OLED on with the programmed current.
- The rise and fall times of SEL1 and SEL2 should be designed to compensate for feed-through.

An example of the proposed array architecture implemented with a with 3-TFT pixel circuit is shown in Figure 11. The 3-TFT circuit can be replaced by any other current programmed circuit.

External Feedback and Compensation for Enhanced Stability

The part of the invention provides a current driving system for AMOLED displays with active current feedback. The current feedback of the driving circuit provides controllable constant current for the organic light-emitting device (OLED), which is not affected by the variations of transistor parameters such as threshold voltage. The current driving circuit includes a current driving transistor and a resistor to change the driving current to voltage and two switching transistors that connect the driving circuit to an external controlling system, as shown in Figure 12.

Figure 12 shows an example of the proposed current pixel circuit along with a section of the column driver circuitry. It shows that the image data can be in the form of an analog voltage signal, which is ideal for use with LCD column drivers.

The feedback pixel circuit consists of three transistors (T1-T3), one resistor (Rf) and one organic light emitting diode (OLED). The storage capacitance, Cs, drawn by dashed-line also may be added to the circuit to store the gate voltage of T1. T1 to T3 can be either amorphous silicon, poly silicon, or organic thin film transistors (TFT) or standard NMOS in CMOS technology or even organic tin film transistors. The Rf resistor also can be made of any proper layer in the fabricating technology with enough stability. In amorphous silicon technology, this resistor can be made of N+ amorphous silicon.

Each pixel has one row control line (Vsel) and two column control lines, Vdata and Vfb.

The external controlling system in its simplest form can be a an operational amplifier in negative feedback connection as illustrated in Figure 13.

The pixel circuit has to operational modes; writhing mode and hold mode. In writing mode, the external circuitry, 'writes' the desired current to the pixel. In hold mode, the pixel is disconnected from external circuits but maintains the current of the OLED until the next writing cycle.

During writing mode, the Vsel signal goes high, turning on T2 and T3. As a result, the driving TFT, T1, along with the external OPAMP and Rf resistor makes a feedback circuit. Because of the high gain of the OPAMP, the voltage at the gate of T1 is adjusted by the feedback loop so that the voltages at the negative and positive inputs of the OPAMP become equal. After the initial transients, the voltage at the node F (Vf) becomes equal to Vin, which is the voltage of the positive input of the OPAMP so the current passing through OLED as well as T1 is

$$Ioled = \frac{Vin}{Rf} \quad (1)$$

In steady state, no current goes through T2 and T3 so there will be no voltage drop from source to drain of these TFTs. Consequently, the output voltage and the voltage of inverting pin of the OPAMP (Vfb) are transferred to gate and source of T1 without any considerable drop.

As long as T1 is in saturation region, any change of threshold voltage and other parameters of this TFT do not influence the OLED current since the high-gain feedback loop stabilizes the current by forcing a constant voltage on Rf resistor.

The current feedback pixel circuit can provide more stable current compared to prior designs because the OLED current is not dependent on the TFT parameters but the Rf resistance which can be much more stable.

When Vsel goes low, T2 and T3 turn off and the feedback loop is disconnected. But the saved voltage on the gate of T1 by the internal gate-source capacitance of T1 or an external capacitor (Cs in Figure 12) maintains the same amount of current passing through T1 as well as the OLED.

In the architecture of Figure 13, the current of the pixel depends on the absolute value of Rf, which is not desirable due to inherent inaccuracy of integrated resistors. The problem can be solved by adding a reference resistor and an external reference current source to each column. Figure 14 shows the proposed scheme for a column.

The external reference current source here provides the programming current and its current passes through the Rref. The voltage of the Rref now is used as the input voltage of the positive input of the OPAMP (Vin). During the writing period of each pixel, the reference current injects the programming current of each pixel (Idata) to Rref Thus the Vin voltage now is

$$Vin = Rf.Idata \qquad (2)$$

Combining the above equation with (1), the current passing through the pixel in writhing mode is:

$$Ioled = Idata\frac{Rref}{Rf} \qquad (3)$$

The above equation indicates a considerable improvement in the accuracy of the programming current because now it depends on the ratio of the resistors in the same substrate instead of the absolute values of the pixel resistors.

Simulation Results

To prove the functionality of the design, the pixel circuit of Figure 12 was simulated using TFT and OLED veriloga models in cadence environment.
In the simulations, Vdd is 30V and Vsel goes up to 30V during the writing mode. The gain and unity-bandwidth of the OPAMP are 10000 and 100kHz consecutively.

Figure 15 shows the waveforms of the pixel current when the reference current is 5uA. At writing mode, the pixel current is very close to reference current, but when the Vsel signal goes low and the circuit mode changes to hold mode, the current level drops to a lower value due to charge injection and clock feed-through effects, introduced by T2 switch.

Use of a Dummy Cell to reduce charge injection/feedthrough:

Several methods have been used to reduce the charge injection and clock feed-through effects in integrated circuits. As the simplest approach, a dummy TFT driven by the inverse signal of Vsel connected to the gate of T1 can reduce both charge injection and clock feed-through errors caused by T2. Figure 16 shows the proposed method. The width of T4 TFT is half of the width of T2.

Figure 17 shows the output current waveform of the modified circuit with and without the dummy TFT.

Stability and lifetime issues:

It has been proved that under forward gate bias, the threshold voltage of amorphous silicon TFTs increases by time. The change of threshold voltage by time is the main reason of instability of the pixel current and limited lifetime of pixel circuits. Although the proposed current feedback cell is insensitive to threshold voltage variation of the TFTs, if the threshold voltage of T1 transistor goes higher than a certain level, the circuit cannot work properly.

As the threshold voltage of T1 in Figure 12 increases, the gate voltage of T1, (Vg) increases. The increment of Vg can disturb the normal operation of the pixel circuit by either forcing the T1 to linear region or preventing T2 to conduct during writing mode.

The voltage at the gate of T1 can be calculated from the following equation

$$Vg = Rf.Io + Vgs1 \qquad (4)$$

where Io is T1 current. Based on current-voltage relationship of TFT transistor:

$$Io = k(Vgs1 - Vt1)^{\alpha} \qquad (5)$$

Vg voltage can be calculated as a function of T1 threshold voltage and output current:

$$Vg = Rf.Io + Vt1 + \left(\frac{Io}{k}\right)^{\frac{1}{\alpha}} \qquad (6)$$

The turn on condition of T2 switch is:

$$Vsel - Vg > Vt2 \qquad (7)$$

Substituting (6) in (7), the condition of (7) is modified as follow:

$$Vsel > Vt1 + Vt2 + Io.Rf + \left(\frac{Io}{k}\right)^{\frac{1}{\alpha}} \qquad (8)$$

The saturation condition of T1 in the pixel circuit is as follow,

$$Vdd - Voled > \alpha_{sat}(Vg - Vt1) \qquad (9)$$

where Voled is the drop of voltage on OLED, and αsat is the saturation factor of TFTs (in CMOS $\alpha sat = 1$)

substituting(6) in (9) , the saturation condition of T1 is as follow

$$Vdd > Voled + \alpha_{sat}\left[\left(\frac{Io}{k}\right)^{\alpha} + Io.Rf\right] \qquad (10)$$

if Vsel amplitude is equal to Vdd, for nominal values of TFT threshold voltage and Voled, the lifetime of pixel is limited by (8).

Connection of OLED to the source of driving TFT:

To enhance reliability, yield, efficiency, and ease of fabrication of the OLED, connection of the anode of the OLED to the source of the driving TFT is preferred. Figure 18 shows a modified version of the pixel shown in Figure 13.

This architecture in many aspects is similar to the pixel circuit of Figure 13, but here, the anode of the OLED is connected to the source of driving TFT (T1). The cathode of the OLED is patterned and connected to the feedback resistor (Rf). During the write mode, the external OPAMP forces a voltage equal to Vin to the Rf resistor through T3 switch; thus in ideal case, the current of the OLED can be calculated from (1). It should be considered that with the same supply and driving voltage levels, the lifetime of the pixel circuit of Figure 18 is less than that of Figure 13. This is due to the voltage at the gate of T1 in the pixel circuit of Figure 18 being higher than the corresponding voltage in the pixel circuit of Figure 13, because of the voltage drop across the OLED. As a result, the T2 TFT in the pixel circuit of Figure 18 becomes disabled sooner compared to the similar T2 TFT in the pixel circuit of Figure 13.

Figure 19 shows the simulation results of the transient analysis of the pixel circuit. The external circuitry and simulation conditions are the same as the simulation conditions of the previously discussed and simulated circuits.

The operating condition of the circuit of Figure 18 can be derived by calculations similar to what has been done for the circuit of Figure 13. In the architecture of Figure 18, the T1 TFT always operates in saturation region as its drain is directly connected to Vdd. The lifetime of the circuit is limited by the turn-on problem of T2 as the gate voltage of T1 goes high. Here the working condition of the pixel can be derived from the following inequality:

$$Vsel > Vt1 + Vt2 + Voled + Io.Rf + \left(\frac{Io}{k}\right)^{\frac{1}{\alpha}}$$

Compared to (3), the above condition is more difficult to meet in order to have the same lifetime. Therefore, Vsel voltage should be higher than that of Figure 18.

Further modifications:

If the fabrication technology provides P-type transistor, the current feedback concept can be implemented in more configurations than the presently stated embodiments. Figure 20 and Figure 21 show two pixel circuits with current feedback in which the feedback resistor (Rf) is connected to Vdd. In the circuit of Figure 20, the driving transistor (T1) is N-type but the feedback-switching transistor (T3) is P-type. In the circuit of Figure 21, both T1 and T3 are P-type and T2 can be N or P type based on operational conditions.

One advantage of this approach over previous circuits is that this circuit can provide increased lifetime by avoiding series connection of Rf and OLED. Another advantage of this modified circuit is that the cathode of the OLED does not need to be patterned.

While particular embodiments of the present invention have been shown and described, changes and modifications may be made to such embodiments without departing from the true scope of the invention.

What is claimed is:

1. A pixel circuit for use in a display comprising:
   an organic light emitting diode (OLED)
   a pixel driver for driving the OLED, having a drive TFT; and
   a compensation circuit for compensating for the shift of the threshold voltage of the drive TFT
2. The pixel circuit according to claim 1, wherein the pixel driver comprises of three TFTs
3. The pixel circuit according to claim 1, wherein the pixel driver comprises of four TFTs, two of which are in the current mirror configuration, and the circuit uses a split-OLED configuration wherein there are two OLEDs in the circuit, each connected to each side of the current mirror structure.
4. The pixel circuit according to claim 1, wherein the pixel driver comprises of four TFTs, two of which are in the current mirror configuration, and the circuit has the OLED connected to the source terminals of each TFT in the current mirror structure.
5. The pixel circuit according to claim 1, wherein the pixel driver comprises of three TFTs, and the circuit is programmed using a current sink, and the OLED is connected to the source terminal of the n-channel drive TFT
6. The pixel circuit according to claim 1, wherein the pixel driver comprises of five or more TFTs, and the circuit incorporates in-pixel redundancy to reduce Vt shift in the TFTs
7. An current programmed array architecture comprising a constant current source and a variable current sink, which are connected to supply the difference in current to the pixel circuit.
8. The array architecture according to claim 6, wherein the variable current sink is implemented on-panel
9. The array architecture according to claim 6, wherein the constant current source is implemented on-panel
10. The array architecture according to claim 6, wherein the pixel circuit is current programmed
11. The array architecture according to claim 6, wherein the variable current source is controlled by an analog voltage
12. The array architecture according to claim 6, wherein the variable current source is controlled by the output of AMLCD drivers

13. An external compensation scheme comprised of a feedback system from a pixel or pixels in the array, and an external compensation circuit that adjusts the input data voltage or current of the pixel circuit according to changes in the Vt of the TFTs
14. The external compensation scheme according to claim 12, wherein the feedback from the pixel or pixels is provided by a feedback resistor
15. The external compensation scheme according to claim 12, wherein an operational amplifier is used in the external circuit for compensation based on the feedback signal
16. The external compensation scheme according to claim 12, wherein multiple feedback resistors are used in such a way as to reduce the impact of resistor value variance
17. The external compensation scheme according to claim 12, wherein the pixel circuit used for feedback has a dummy TFT to reduce the impact of charge injection/feedthrough from the gate drivers
18. The external compensation scheme according to claim 12, wherein one or more p-channel TFTs are used with the feedback resistor connected between the voltage supply and the drive TFT
19. The external compensation scheme according to claim 12, wherein OLED is connected to the drain terminal of the drive TFT in the pixel circuit, i.e. between the supply voltage and the drive TFT in the case of n-channel drive TFT, and between the drive TFT and ground in the case of a p-channel drive TFT
20. The external compensation scheme according to claim 12, wherein OLED is connected to the source terminal of the drive TFT in the pixel circuit, i.e. between the supply voltage and the drive TFT in the case of p-channel drive TFT, and between the drive TFT and ground in the case of a n-channel drive TFT

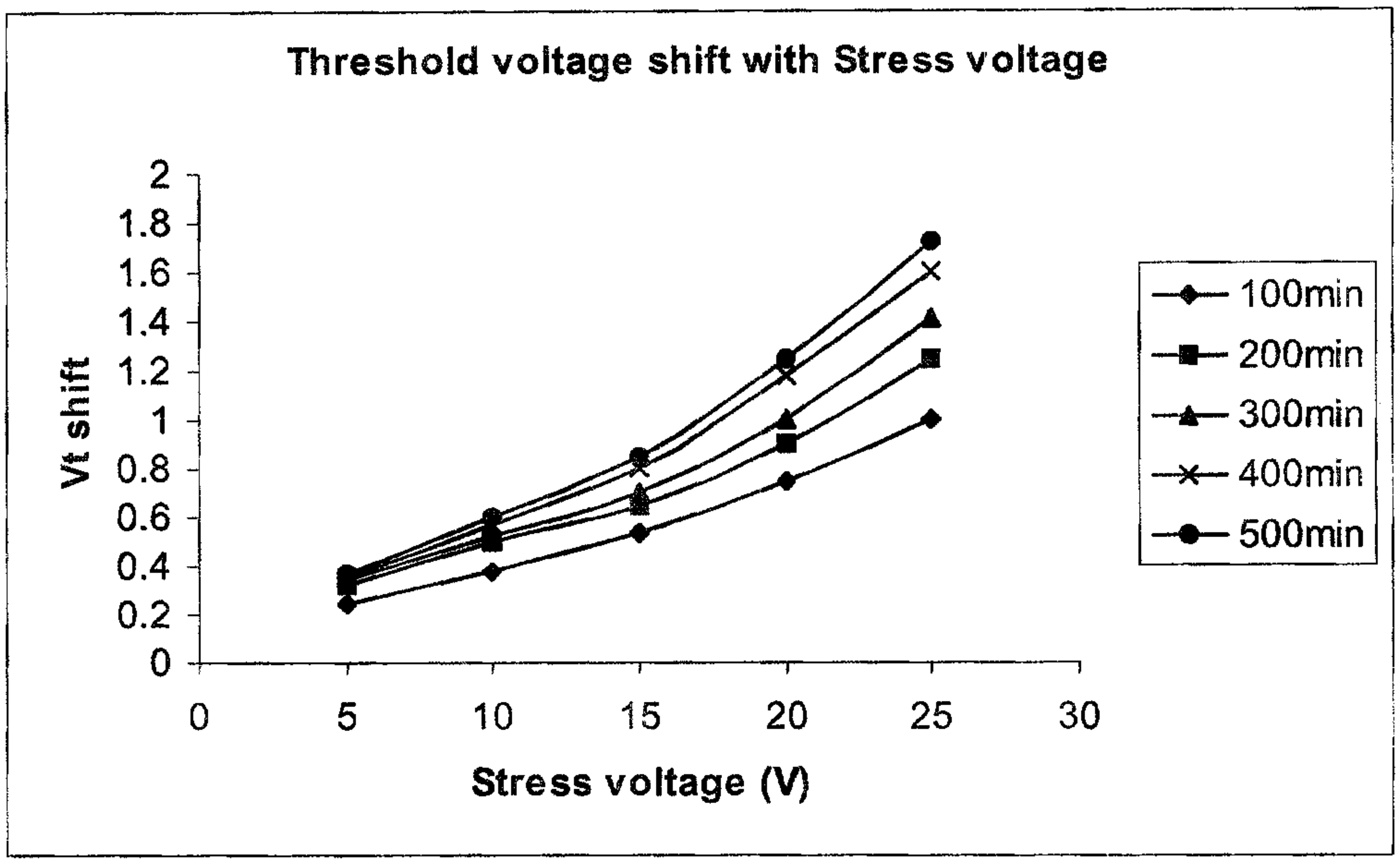

Figure 1 - Threshold Voltage shift vs. Stress Voltage of a discrete a-Si TFT

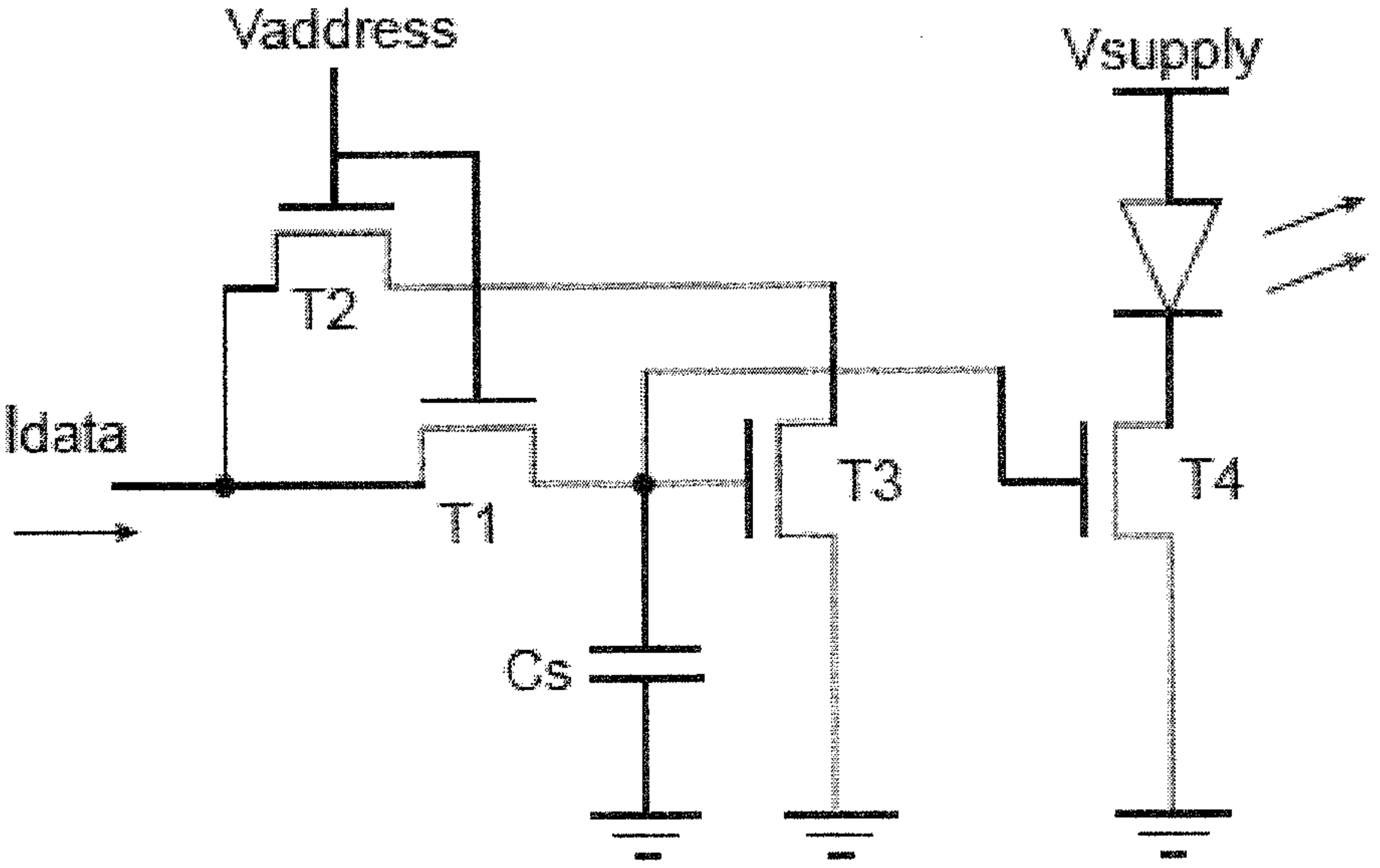

Figure 2 - 4-TFT current-programmed pixel

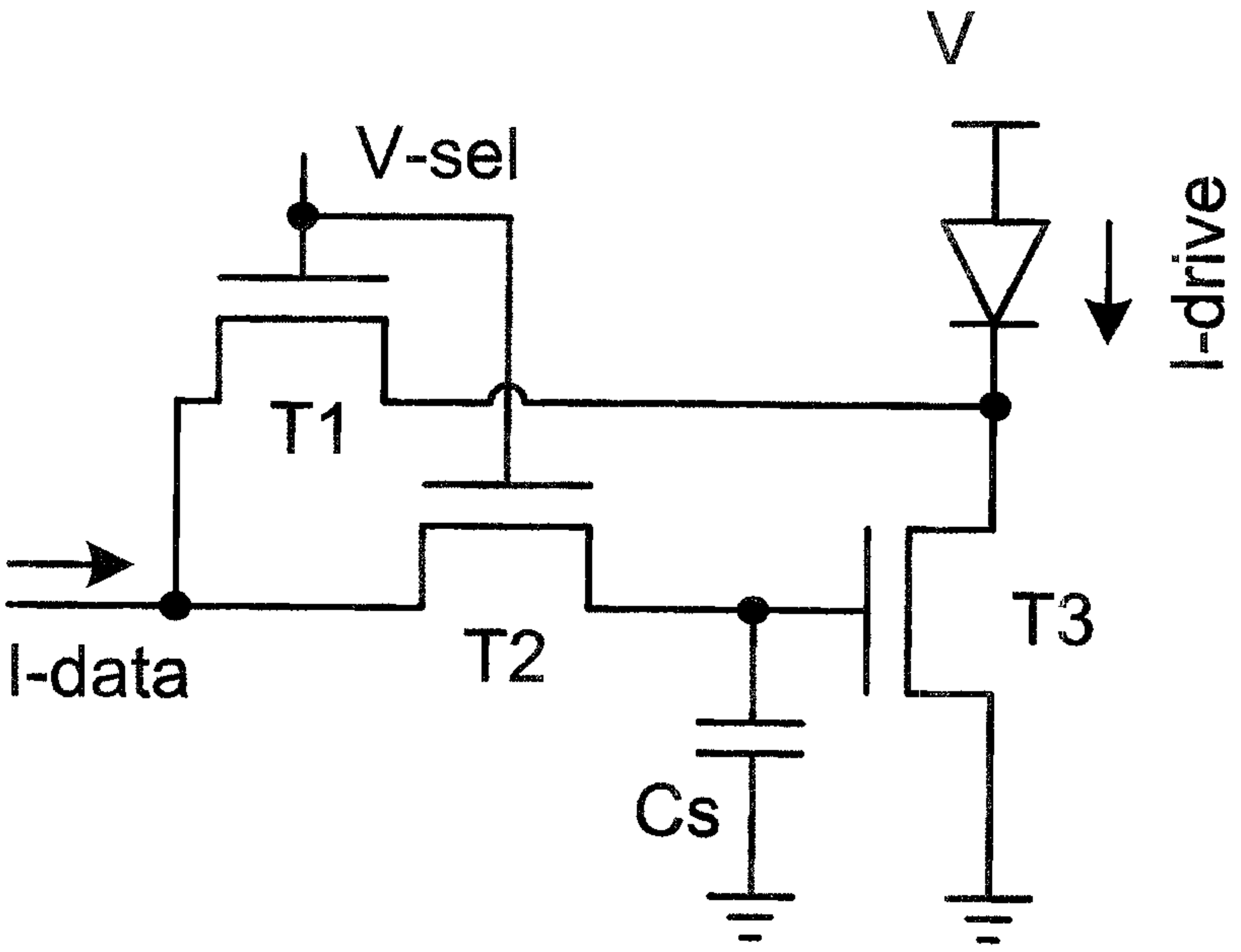

Figure 3 - A 3-TFT current programmed Vt-shift compensating AMOLED pixel circuit

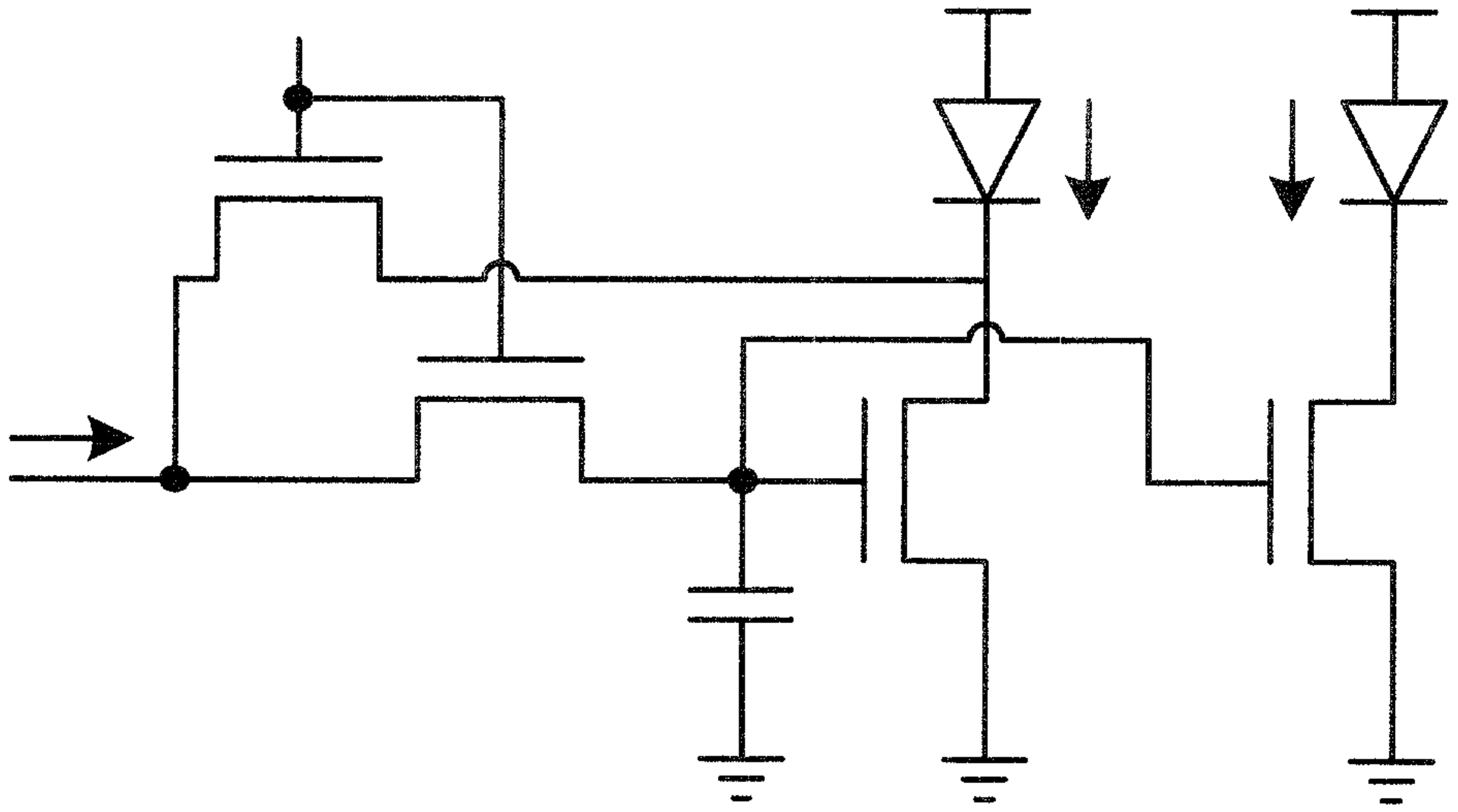

Figure 4 - A 4-TFT split OLED current programmed Vt-shift compensating AMOLED pixel circuit

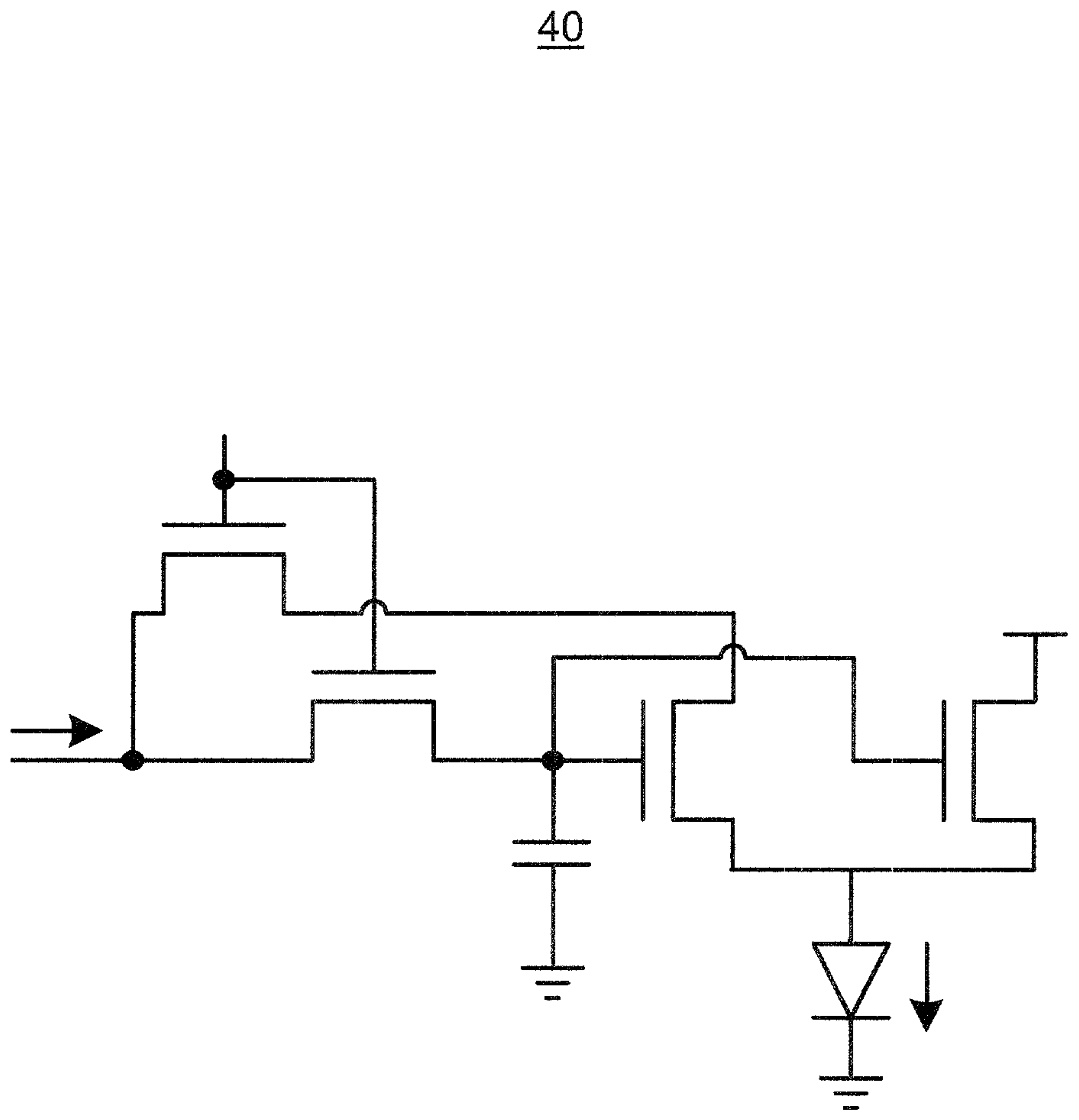

Figure 5 - A 4-TFT split OLED current programmed Vt-shift compensating AMOLED pixel circuit

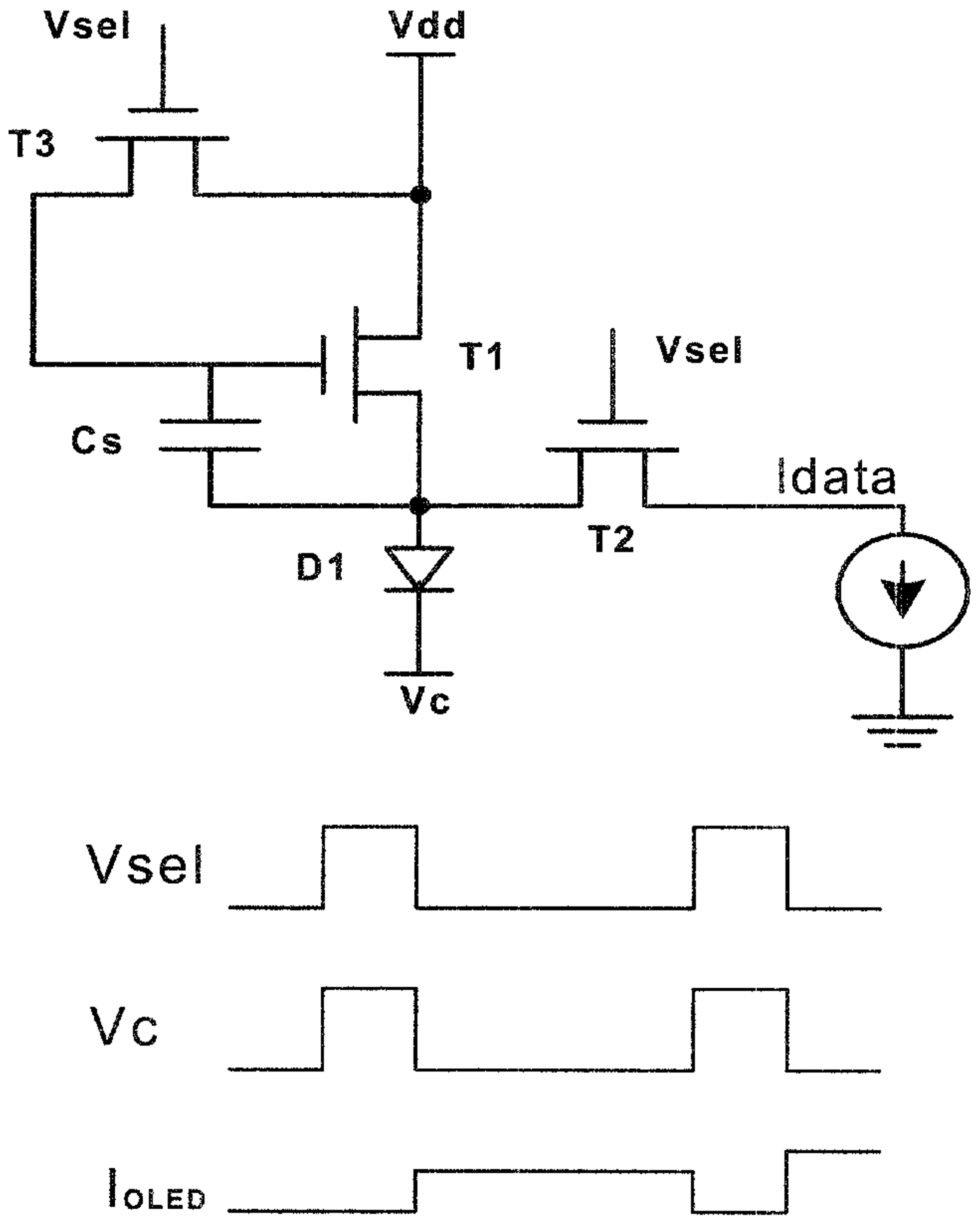

Figure 6 - A 3-TFT current programmed Vt-shift compensating AMOLED pixel circuit

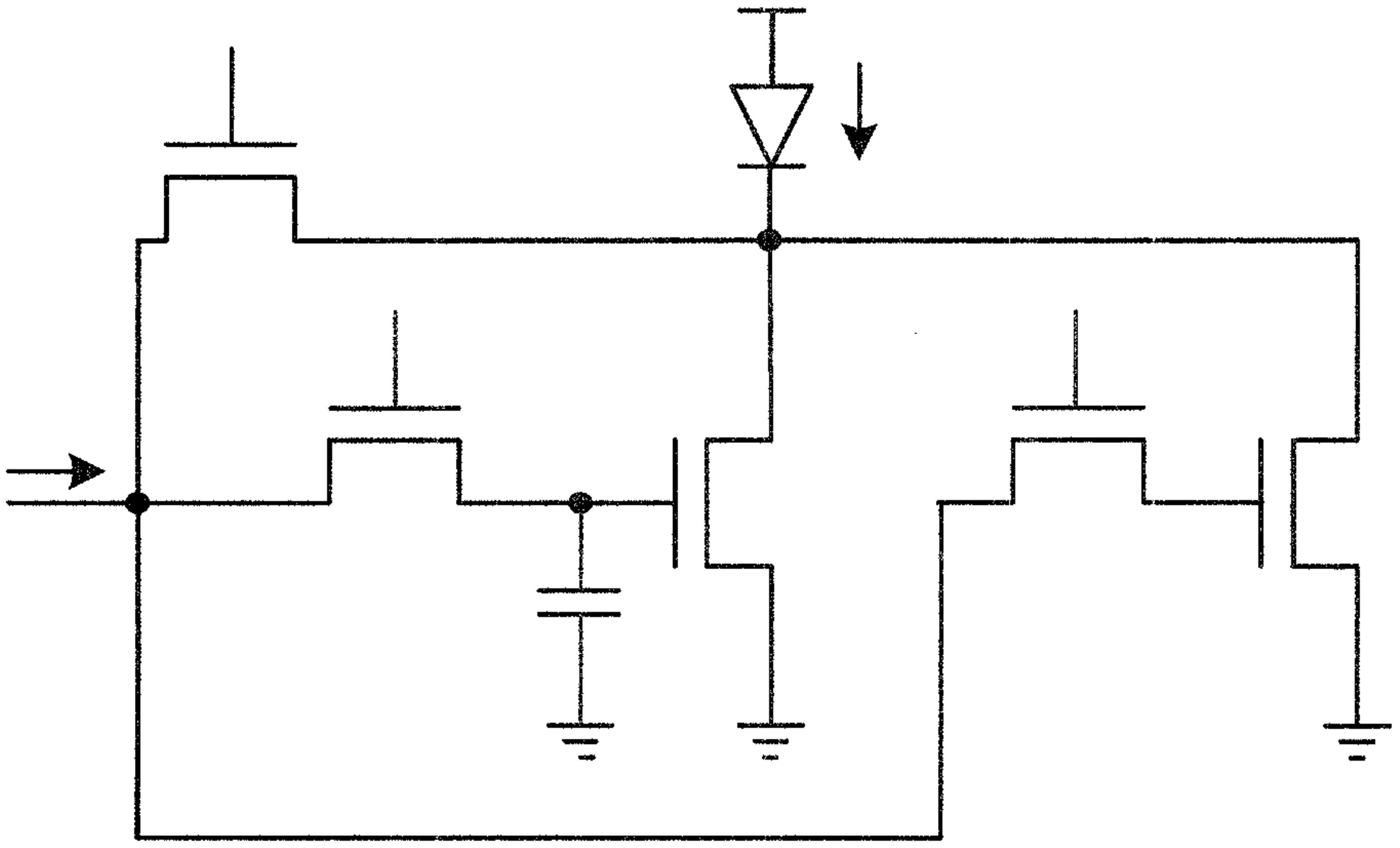

Figure 7 - A 5-TFT current programmed Vt-shift compensating AMOLED pixel circuit with redundancy

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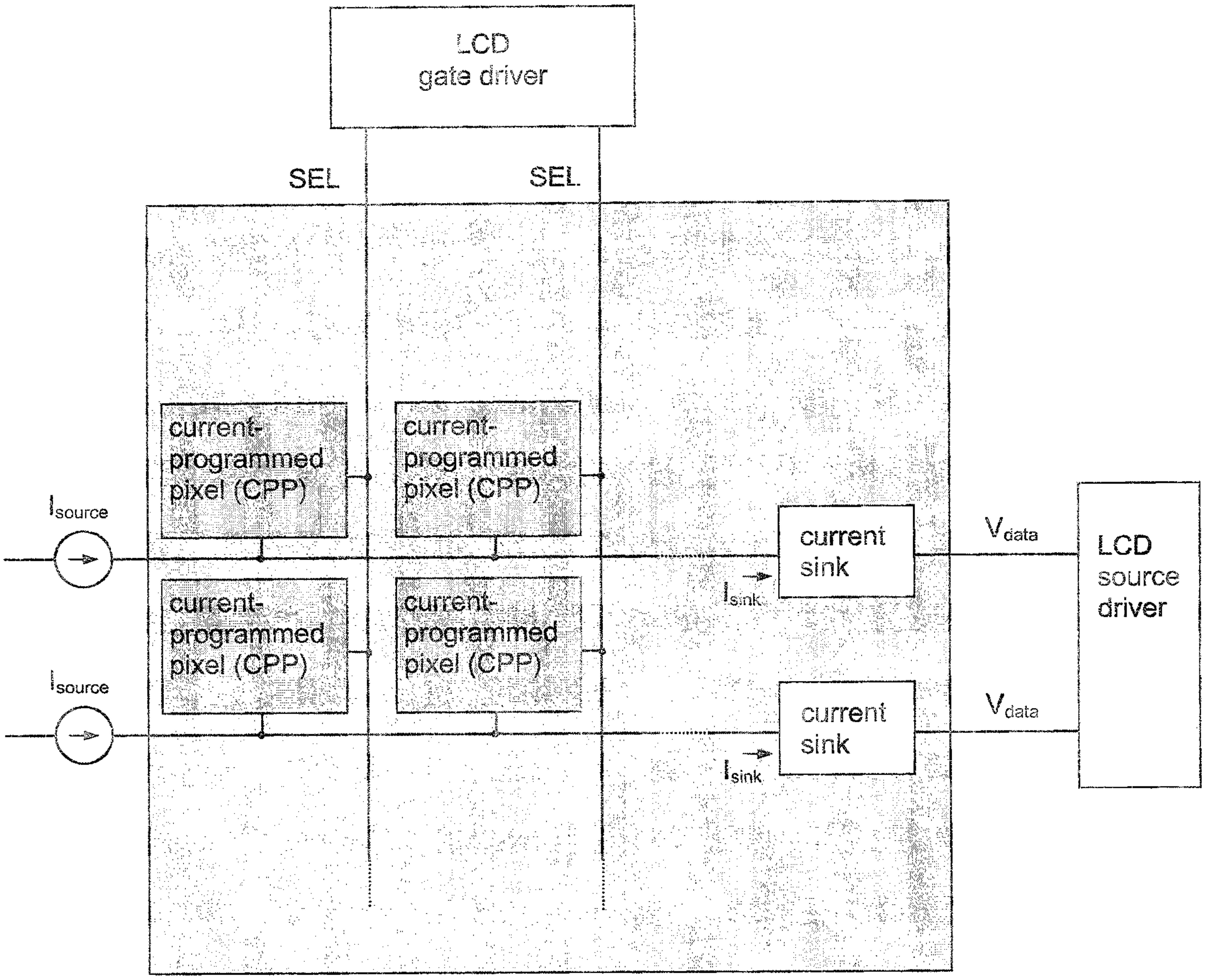

Figure 8 – A new array architecture using current sources and current sinks to drive current programmed pixels

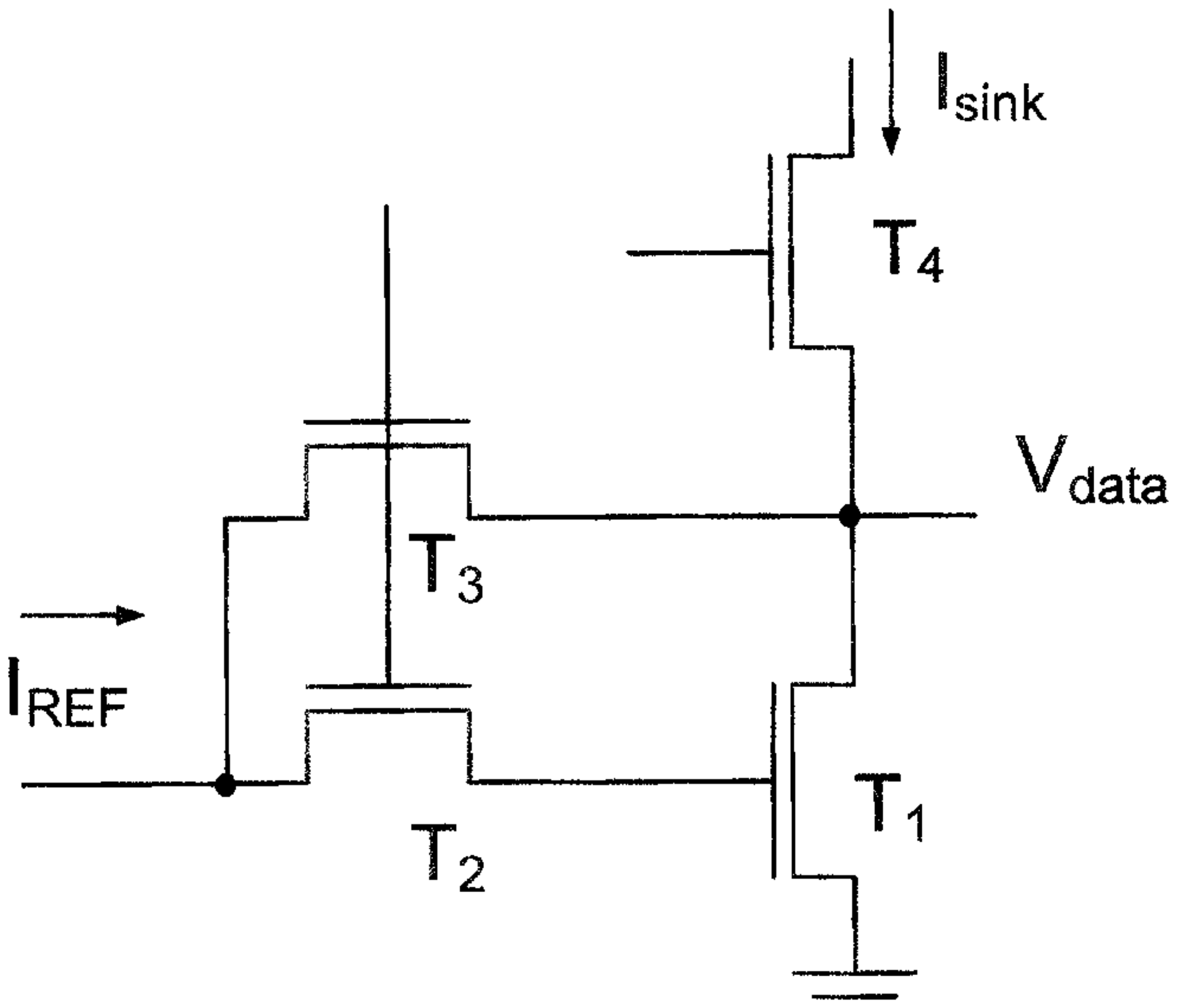

Figure 9 - Schematic of a current sink using n-channel TFTs

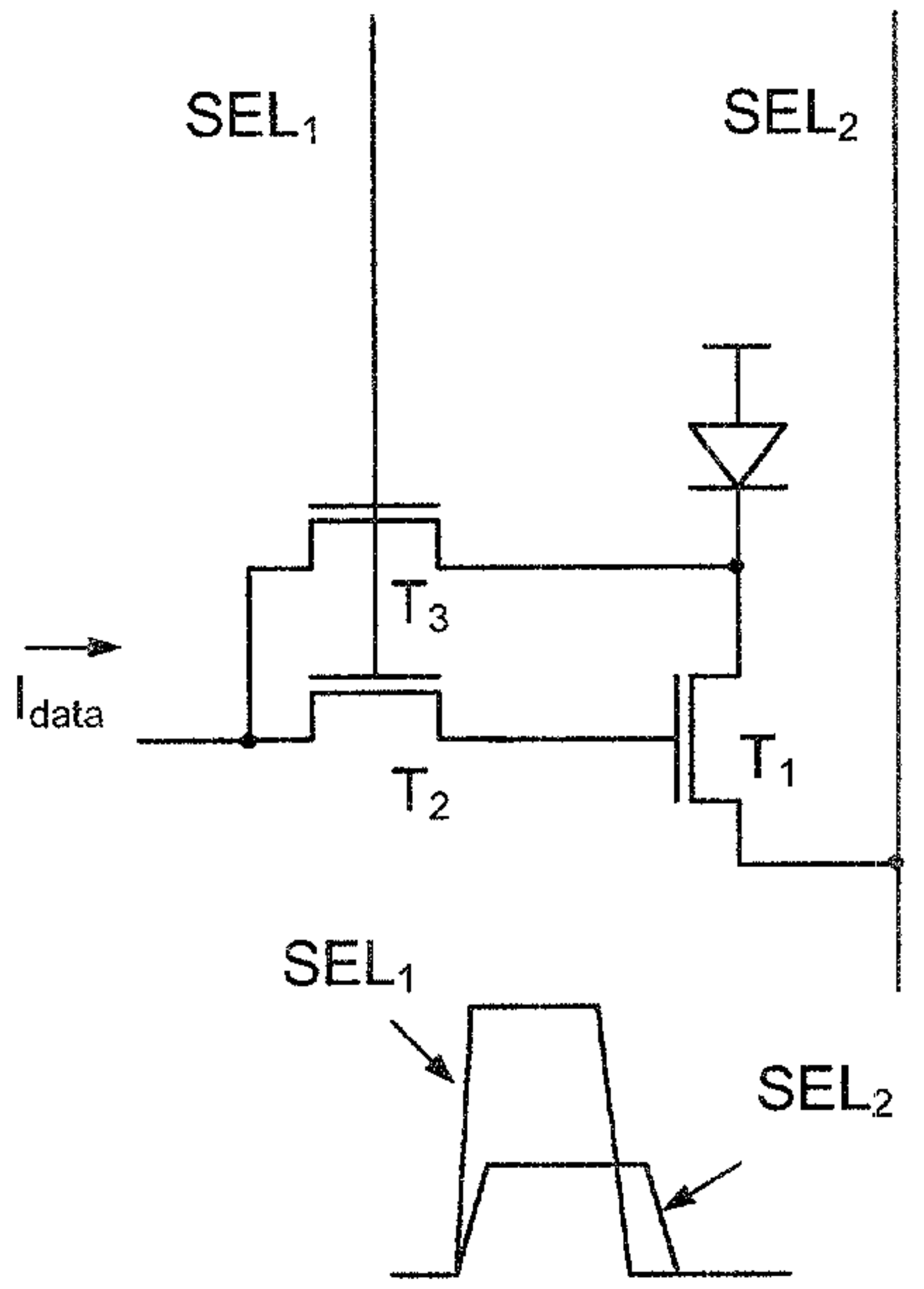

Figure 10 - Schematic of 3-TFT pixel driver circuit with special addressing

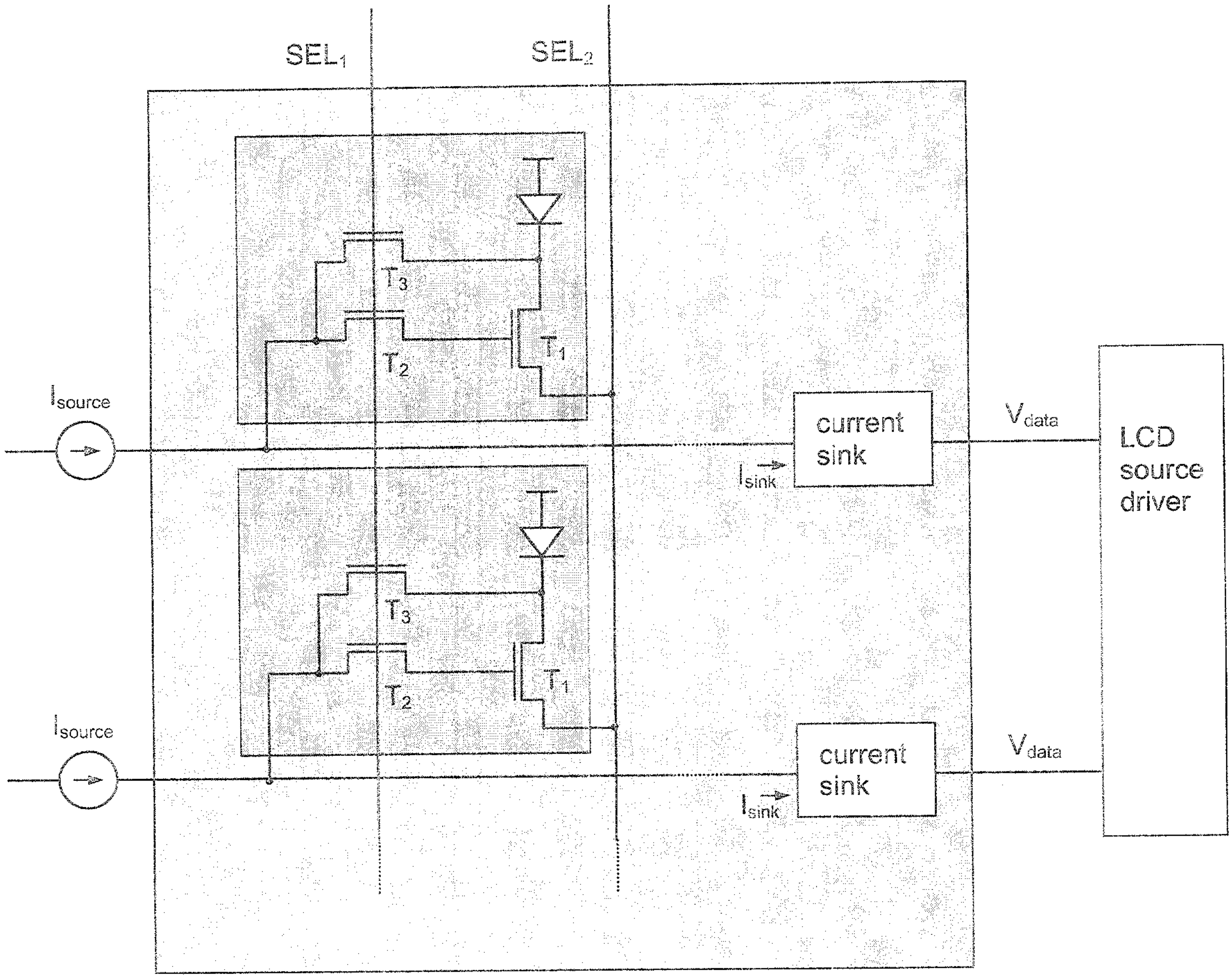

Figure 11 – The new array architecture implemented with the 3-TFT current programmed pixel circuit

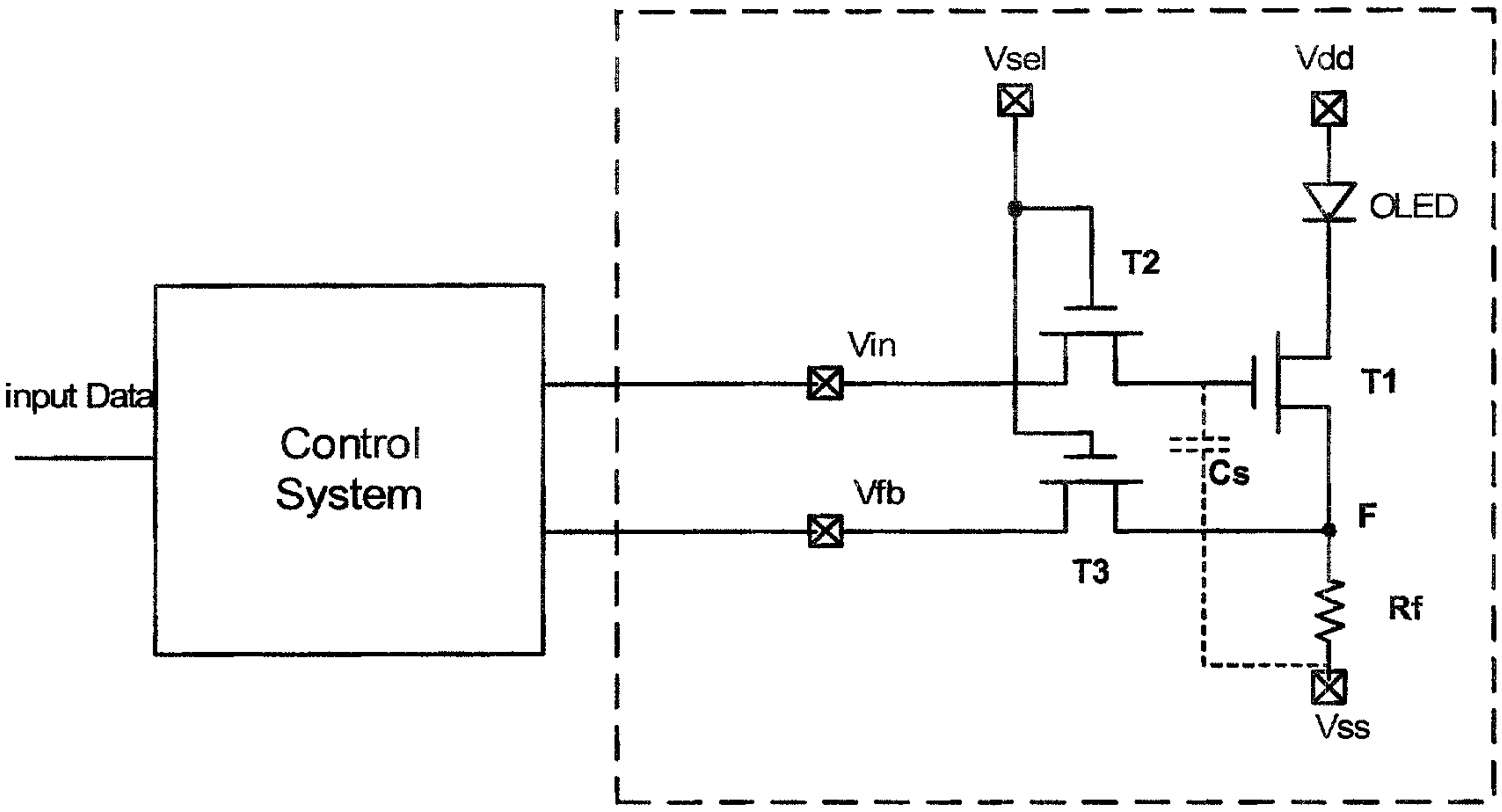

Figure 12 – Schematic of a current feedback pixel circuit with the external control system driving the circuit

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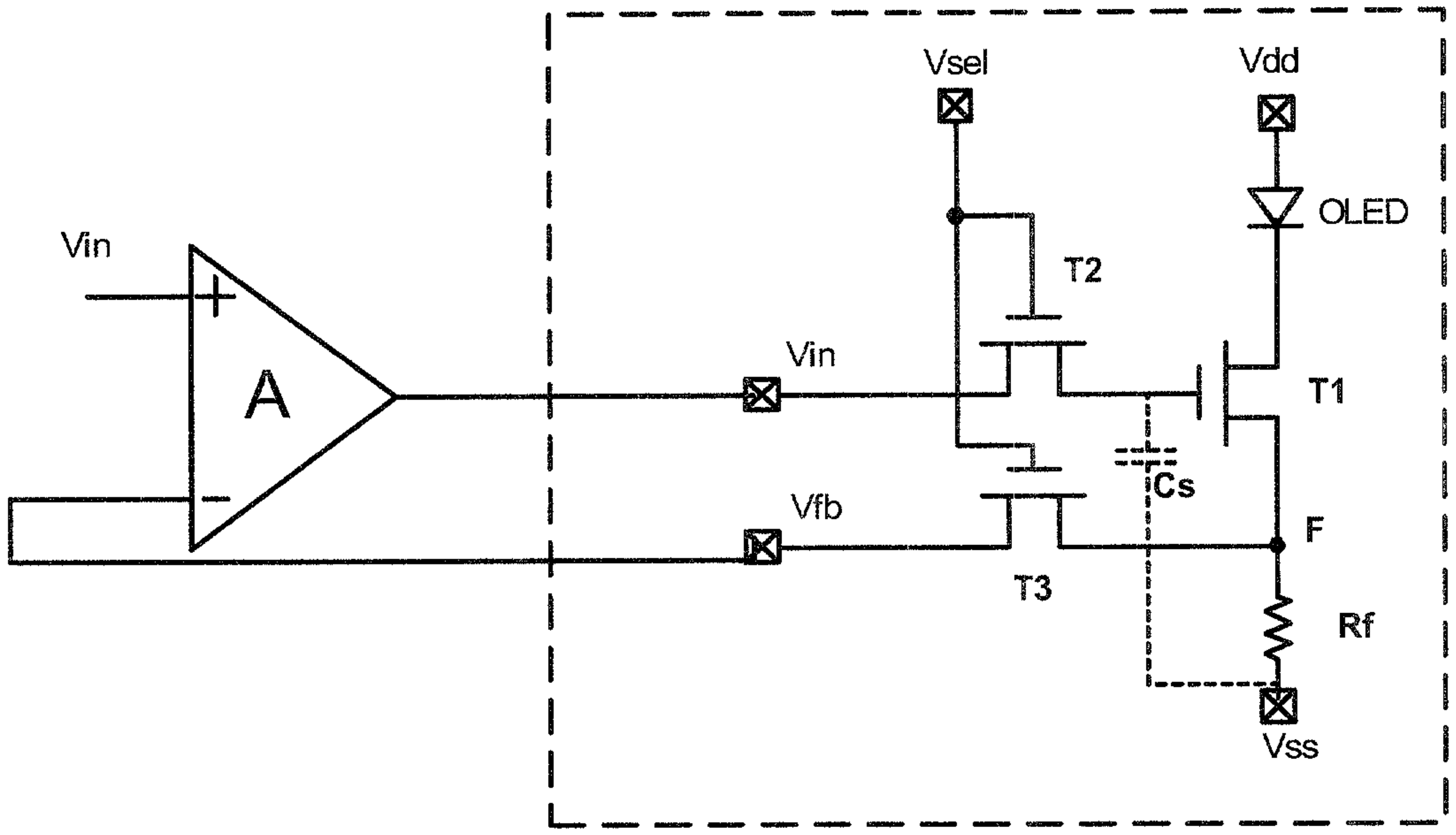


Figure 13 – Schematic of current feedback pixel and an opamp as the external control unit

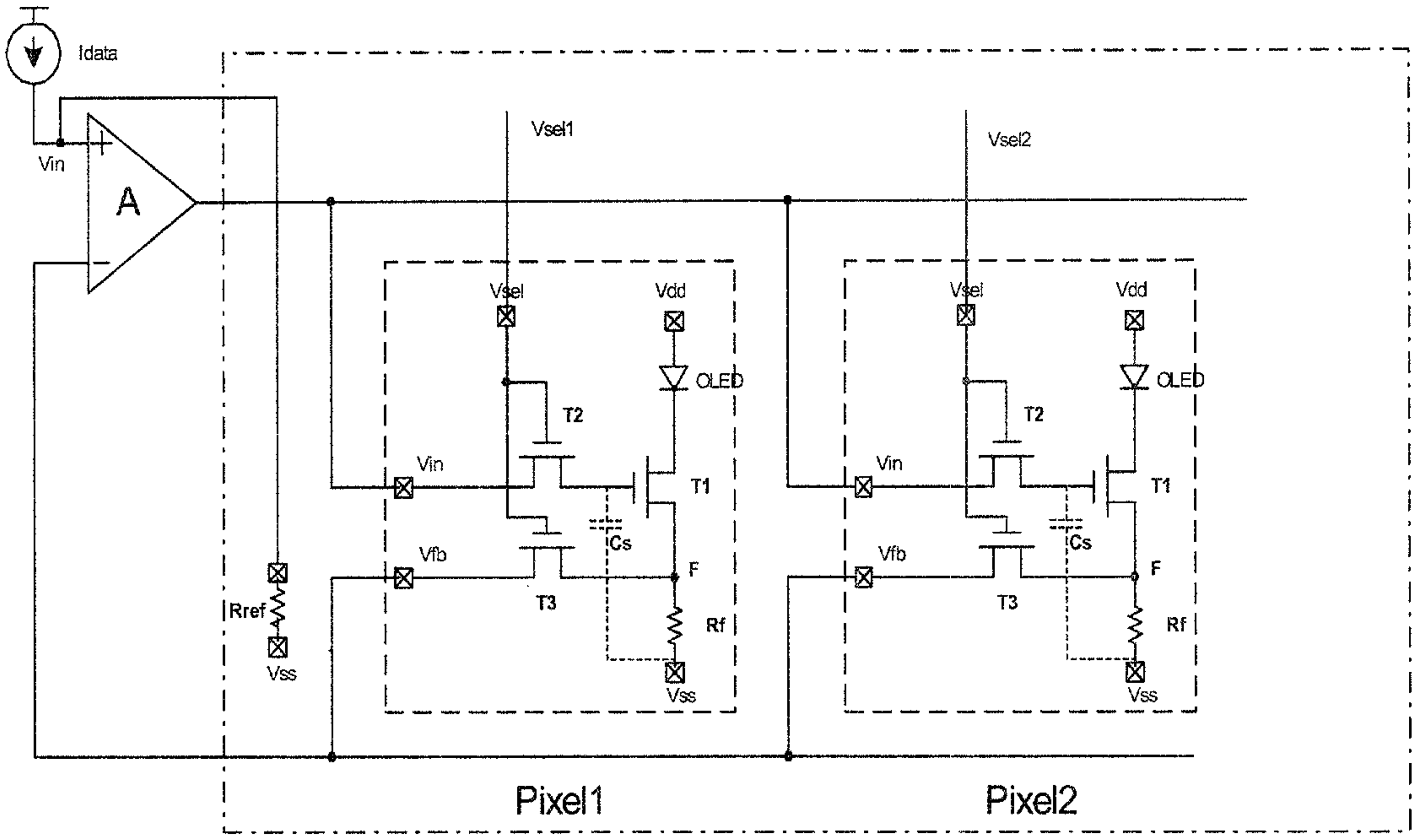


Figure 14 – Schematic of pixel circuits of Figure 11 in the same column as the external driving opamp, reference current source, and reference resistor

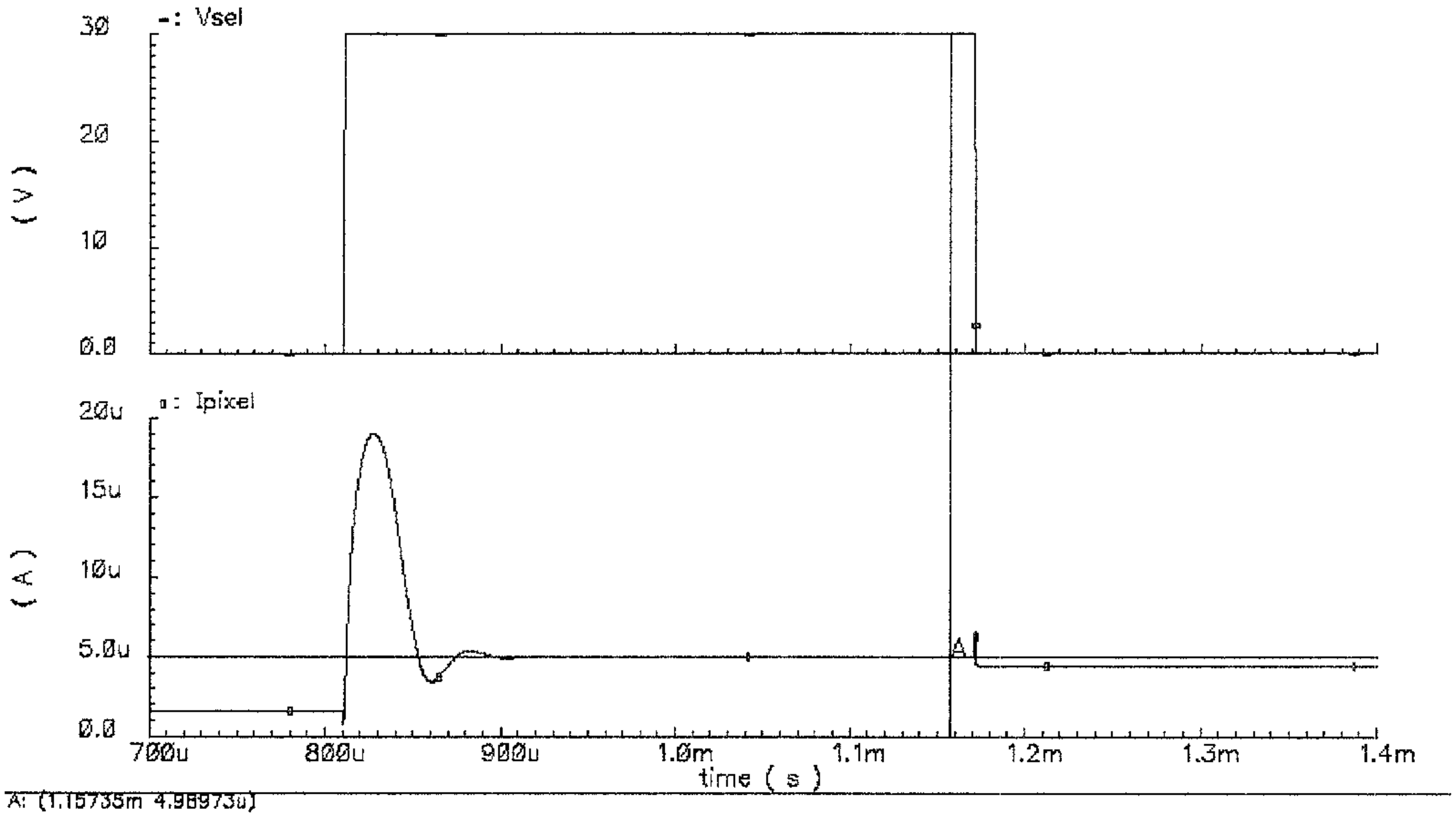


Figure 15 – Simulation waveforms of row select and output current of the pixel of Figure 11

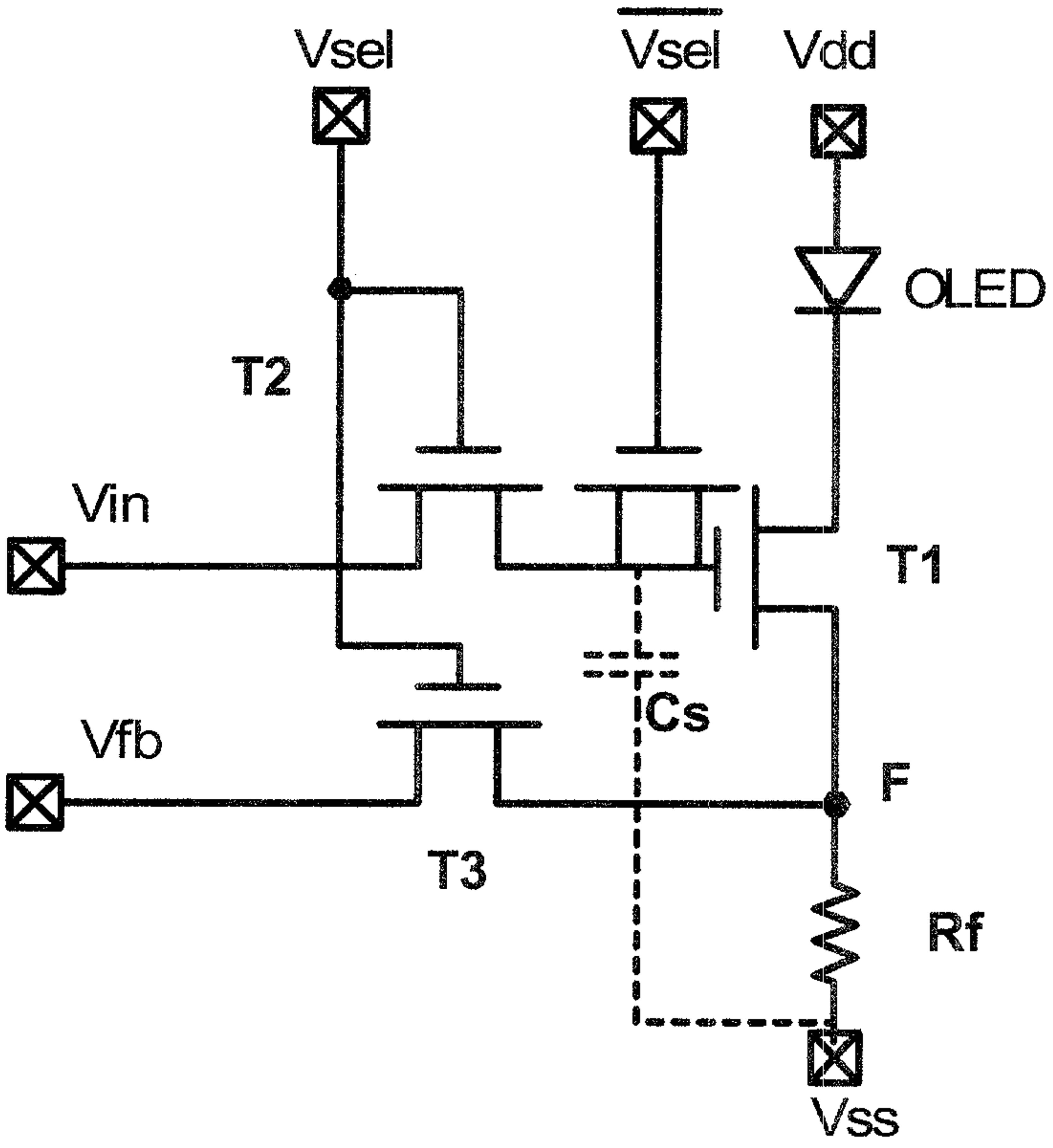


Figure 16 – Current feedback pixel circuit with dummy transistor connected to the gate of drive TFT

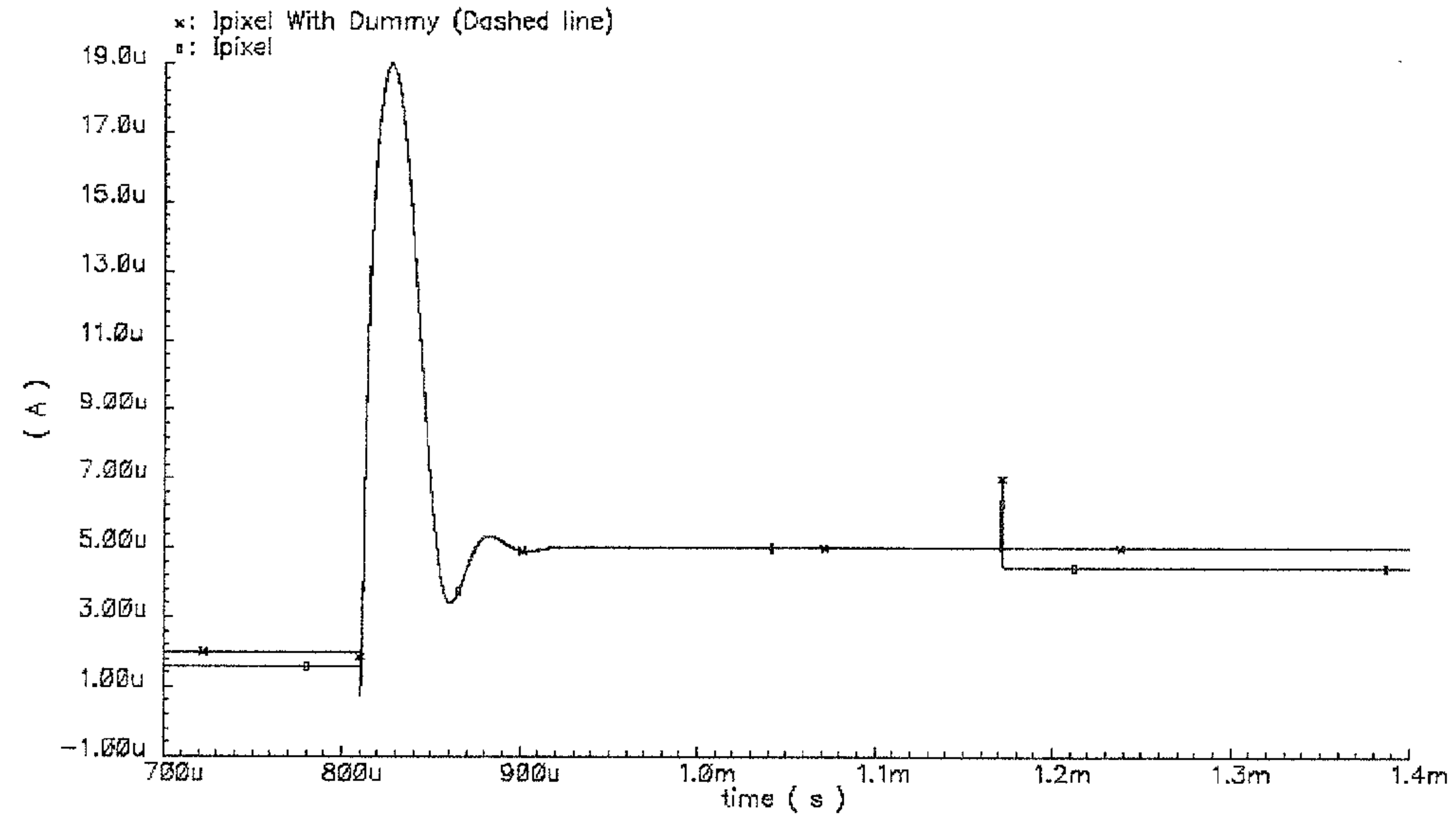


Figure 17 – Simulation waveforms of the output current of the circuit of Figure 15 with and without the dummy transistor

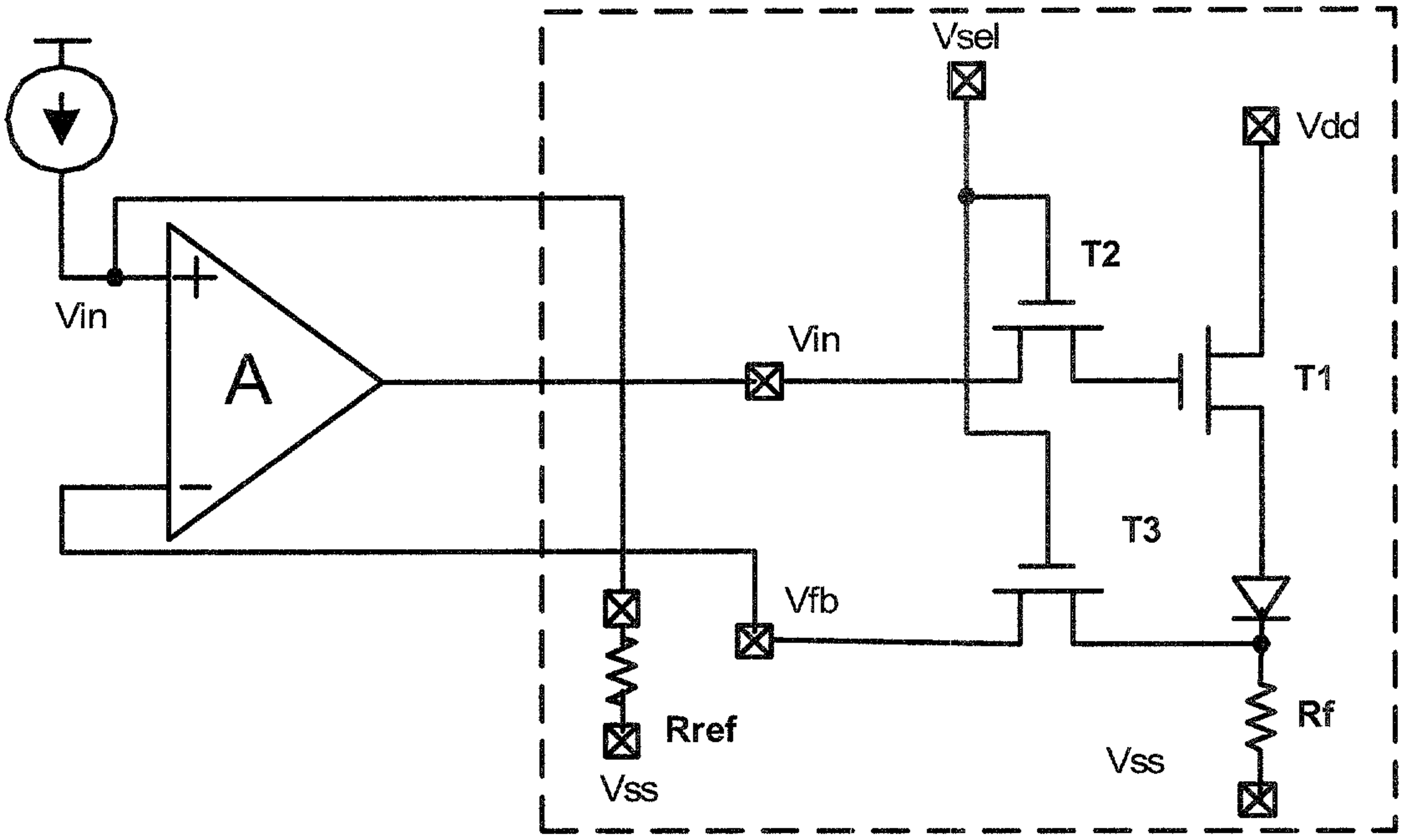


Figure 18 - Schematic of a current feedback pixel circuit with OLED connected to the source of the drive TFT

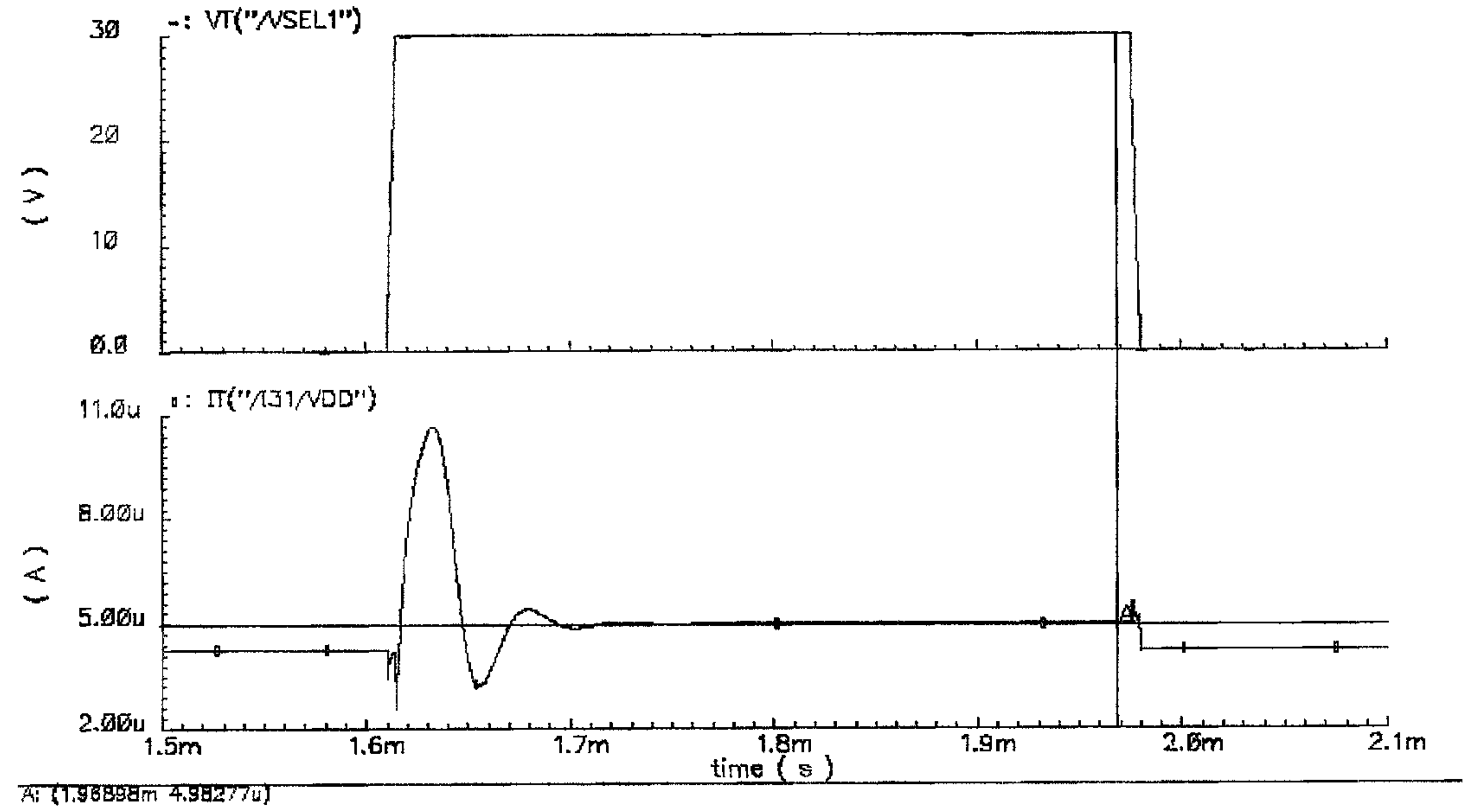


Figure 19 – Simulation waveforms of the circuit of Figure 17

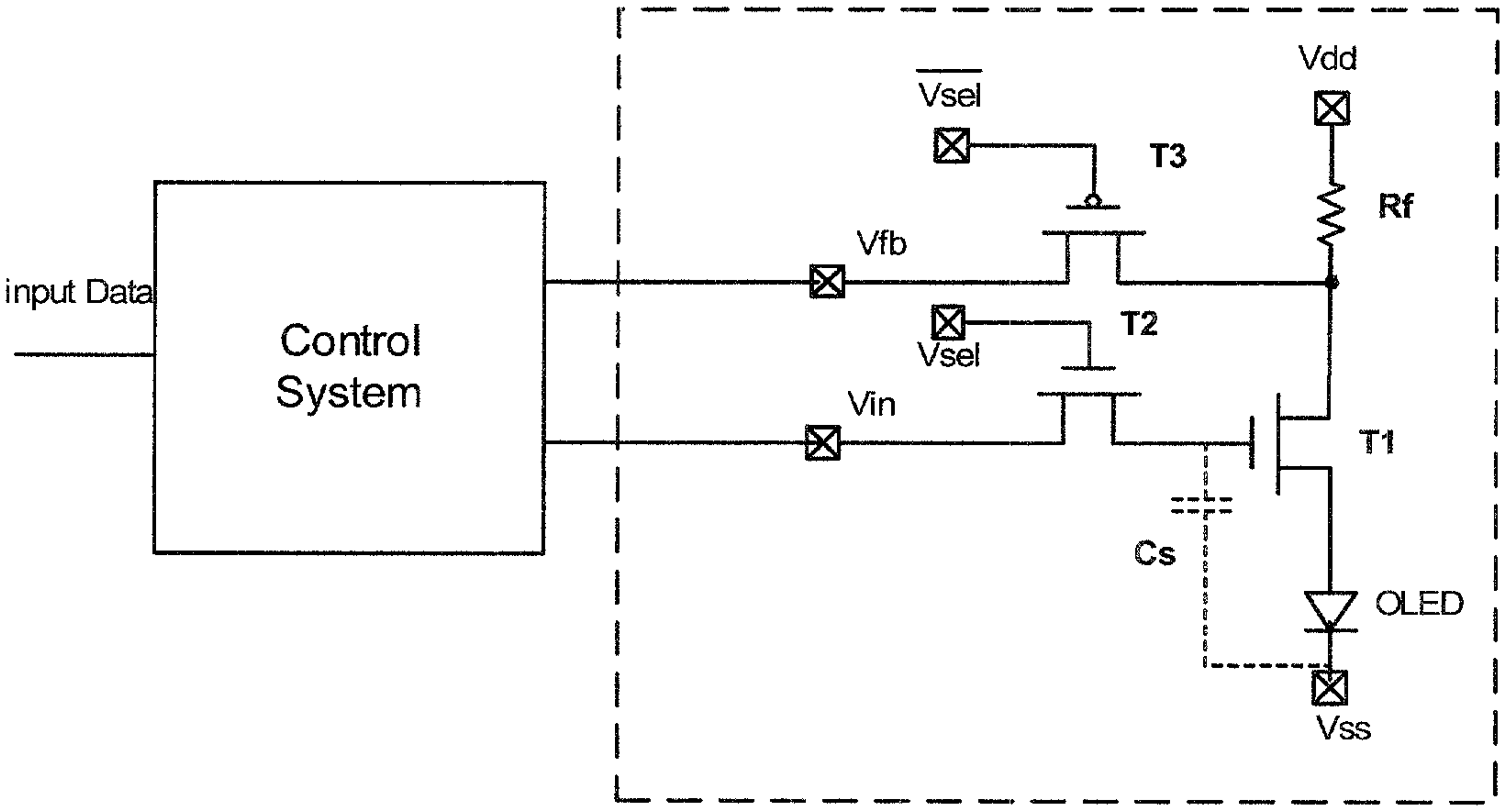


Figure 20 - Schematic of current feedback pixel circuit with its feedback resistor connected to the drain of the n-channel driving TFT and a p-channel feedback TFT switch

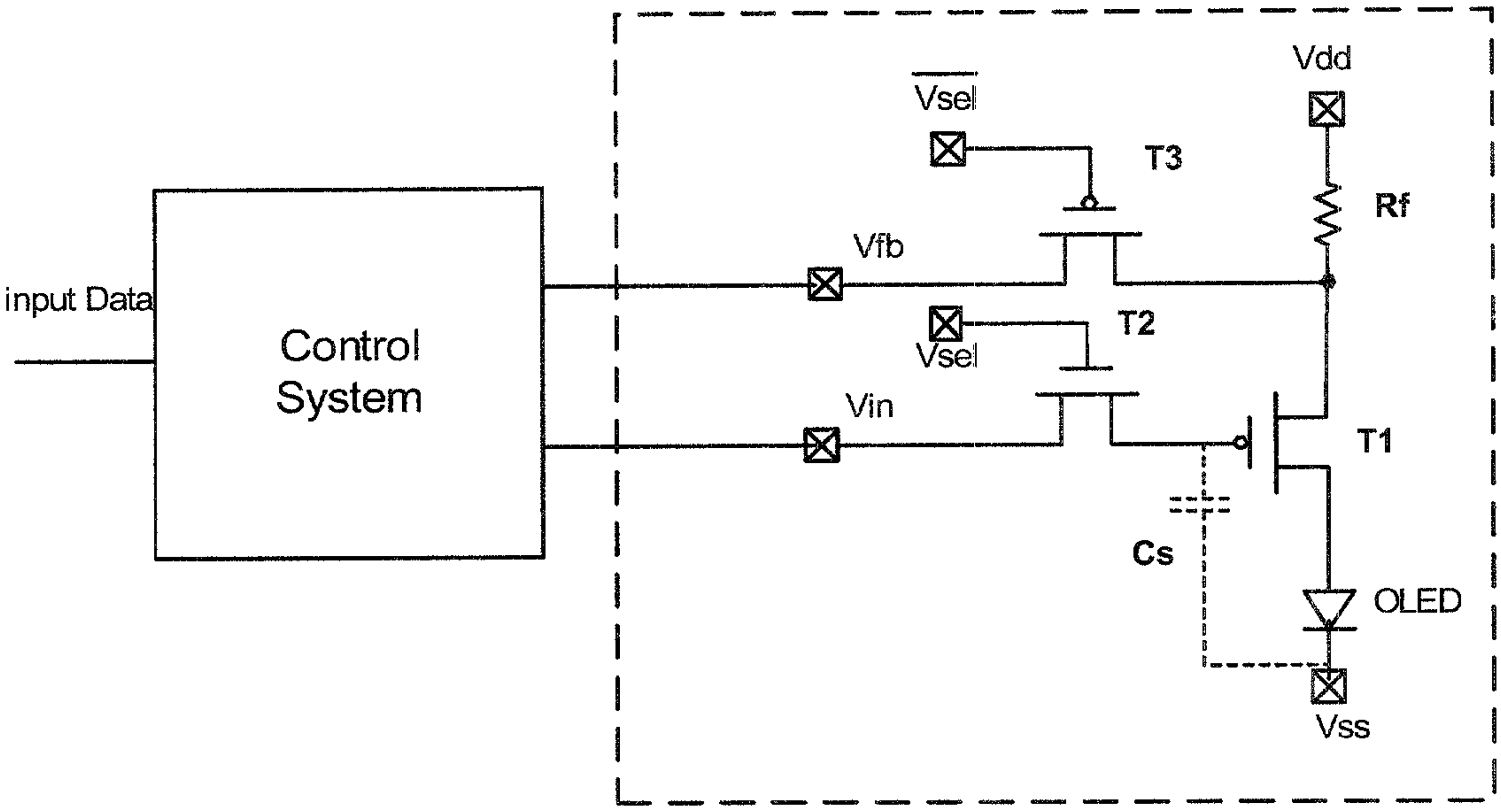
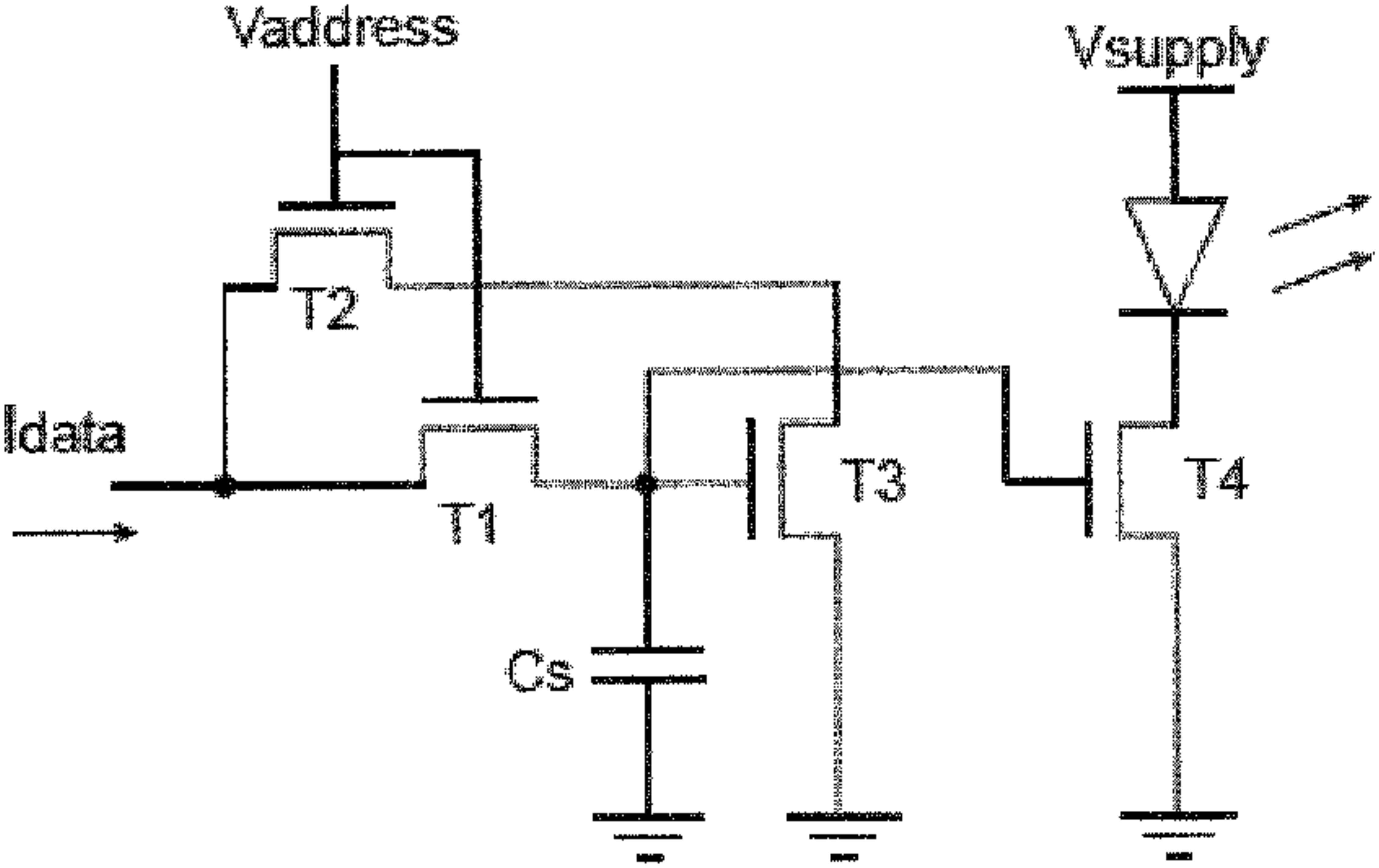


Figure 21 - Schematic of current feedback pixel circuit with its feedback resistor connected to the source of the p-channel driving TFT and a p-channel feedback TFT switch



4-TFT current-programmed pixel