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Thin Film Transistors As Driving Devices for Attached Devices

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TFTs can be used as driving or detecting devices for purposes of optical, chemical, or biological sensing, imaging, displays, etc. Assuming the stability is not an issue, the poly-Si, IGZO, and a-Si:H TFTs were compared with respect to the device driving capability. For the drain-attached device, the maximum available power is determined by the device's resistance and the TFT's on-current. For the gate-attached device, the study is based on connecting a resistor and a capacitor in parallel. The raise or decay of the drain current is dependent on the *RC* time delay. Although the high mobility TFT has many advnatages, the low mobility TFT is adequate for certain applications. In real applications, the manufactuability and cost are important factors in choosing the TFT.

Introduction

TFTs have been the most popular devices in the large area active matrix liquid crystal displays (AMLCDs) for more than 20 years. The a-Si:H TFT is suitable for driving the liquid crystal in the pixel level not only for its low power consumption, low leakage current, gray scale capability, etc. but also for the simple, low temperature, and high throughput fabrication process [1]. However, the low mobility of ≤ 1 $cm^2/s.v$ greatly restricts its applications in many other products. For example, the OLED can potentially replace the LCD due to the higher brightness, better color quality, and wider viewing angles. Due to the high current requirement, the OLED is impossible to prepare with the one a-Si:H TFT per pixel design. It requires the high mobility TFT [2]. The amorphous indium gallium zinc oxide (a-IGZO) TFT, which has a field effect mobility about one order of magnitude higher than that of the a-Si:H TFT, has been used in AMLCDs, AMOLEDs, and electronic papers [3]. Poly-Si TFTs with very high mobilities, e.g., > 200 cm^2/Vs, have also been demonstrated feasible for these applications and even the integrated circuits (ICs) for many years. In addition to displays, TFTs have been used as the driving devices in optical, chemical, or biological sensing, detection, or imaging, as shown in Table 1 [2-10]. Depending on the specific application, each attached device has its own requirements on the voltage, current, power, etc. Most of the limitations are related to the device's resistance and electrical or physical properties. In this paper, authors investigated limitations of TFTs in driving different types of devices.

Table 1 Properties of devices attached to TFTs

	V	I	Power	Refs.
OLED	15V	10 μA	150 μW	[5]
Liquid Crystal	2V	100 nA	200 nW	[6]
Photo Sensor	5V	$6*10^{-10}$A	3 nW	[7]
Chemical Sensor (K^+)	6.1 V	1 μA	6.1 μW	[8]
Gas Sensor (CO_2)	5V	5 mA	25 mW	[9]
Gas Sensor (H_2)	0.1V	10 nA	1 nW	[10]

TFTs Used in This Study – Characteristics and Preparation Methods

A-Si:H, poly-Si, and IGZO TFTs used in this study were fabricated from different processes. Figure 1 shows their transfer characteristics [11-15]. The corresponding device properties are shown in Table 2.

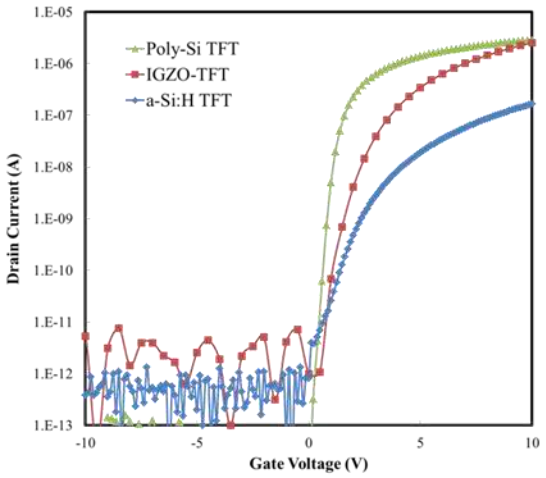

Fig. 1. Transfer characteristics of three types of TFTs [11-15].

Table 2 TFT device properties

Type of TFT	a-Si:H	Poly-Si	IGZO
W/L (μm/μm)	90/11	12/6	20/10
V_{TH} (V)	1.5	0.47	1.5
Mobility (cm^2/Vs)	0.6	235	8.9
I_{ON}/I_{OFF}	$9.2*10^5$	$2.2*10^7$	$1.0*10^7$
S.S. (mV/dec)	986	224	644
Ref.	[11-13]	[14]	[15]

The a-Si:H was fabricated with the 2-photomask process on a Corning 7059 glass [11,12]. It has an inverted staggered tri-layer structure with Mo gate, source, and drain electrodes. The Si_3N_4/a-Si:H/Si_3N_4, tri-layer was deposited by PECVD in one pump down without breaking the vacuum. The self-aligned source/drain contact was defined with a backlight exposure step through the gate pattern. The PECVD n^+ film was used as the ohmic layer for the source and drain electrodes. After the source and drain electrodes were wet etched the n^+ layer was etched with a RIE process. The complete TFT was annealed at 250℃ for 30 minutes in air to remove the plasma damages [13]. The poly-Si TFT was fabricated with the excimer crystallized Si on a

Corning1737 glass [14]. It has a coplanar and LDD structure. After the 50-nm-thick 380℃ PECVD a-Si:H was crystallized with a line-shaped beam of 350 mJ/cm^2 and 95% overlap ratio, source/drain in the LDD region are doped using ion implantation and activated at 530℃ for 1 hour. The gate dielectric was made of a 40 nm thick PECVD SiO_2 and the gate electrode was made of the sputter deposited MoW film. The IGZO TFT has an bottom gate structure on a glass substrate [15]. The 300 nm thick 370℃ PECVD SiO_x gate insulator was deposited on the Ti/Al/Ti gate electrode. After the Ti/Al/Ti source/drain electrodes were formed above the SiO_x, a 30 nm thick a-IGZO film was deposited by dc magnetron sputtering at room temperature using a In:Ga:Zn (1:1:1) target in O_2/Ar at 5 mTorr. The device was passivated with a 200 nm thick PECVD SiO_X film and annealed at 330℃ for 2 hours.

Results and Discussion

Although many types of devices can be attached at different parts of the TFT, in this paper, the discussions are focused on two simplified cases: a resistor attached to the drain electrode of the TFT and a resistor a capacitor attached in parallel to the gate electrode of the TFT.

1. Driving a device attached to the drain electrode of the TFT

TFTs have been used to drive various kinds of devices many of which can be taken as a resistor with specific requirement of power. For some applications, such as the chemical, biological, optical, or mechanical stress sensing, the resistance (r) of the attached device changes with the environment. Figure 2 shows a simple circuit of a TFT with a resistor attached to the drain electrode. Since the device is connected in series with the TFT, the drain current of the latter, i.e., I_D, is the same as the current of the former. The voltage drop across the resistor is the difference between the drain voltage of the TFT, i.e., V_D, and the applied voltage, i.e., V_D'.

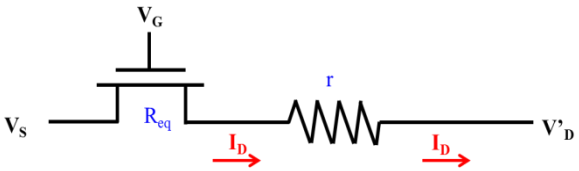

Fig. 2. TFT with an attached resistor.

The I_D of the TFT in Fig. 2 can expressed by the following equation [16]:

$$I_D = \frac{W}{L}\mu C_{OX}\left[(V_G - V_{TH})V_D - \frac{1}{2}V_D^2\right] \quad (1)$$

where W is the channel width, L is the channel length, μ is the field effect mobility, C_{ox} is gate dielectric capacitance, V_G is the gate voltage, and V_{TH} is the threshold voltage. When a resistor with a resistance r is attached to the drain electrode, the actual drain voltage is:

$$V_D = V_D' - I_D r \quad (2)$$

Eqs. (1) and (2) can be combined into the following equation

$$I_D = A\left[B(V_D' - I_D r) - \frac{1}{2}(V_D' - I_D r)^2\right] \quad (3)$$

where $A = \frac{W}{L}\mu C_{OX}$ and $B = V_G - V_{TH}$.

Therefore, the I_D can be expressed as a function of physical parameters of these devices:

$$r^2 I_D^2 + \left(\frac{2}{A} + 2Br - 2V_D' r\right) I_D + (V_D'^2 - 2BV_D') = 0 \quad (4)$$

$$I_D = \frac{-\left(\frac{2}{A}+2Br-2V_D'r\right) \pm \sqrt{\left(\frac{2}{A}+2Br-2V_D'r\right)^2 - 4r^2(V_D'^2-2BV_D')}}{2r^2} \quad (5)$$

Figure 3 shows the calculated transfer characteristics of a poly-Si TFT attached with a resistor of which the resistance r varies between 10^5 and 10^9 ohm. The curve with the 0 ohm resistance belongs to the actual poly-Si TFT. Below V_G = -0.7V, the TFT is in the off state. The equivalent resistance of the TFT, i.e., R_{eq}, is so high that it dominates the total resistance of the Fig. 2 system. Therefore, the I_D is not affected by the change of r. When V_G is increased, e.g., to above 0 V, the TFT is gradually turned on. The R_{eq} of the TFT decreases with the increase of the V_G and eventually becomes smaller than r. Then, the total resistance system is dominated by the magnitude of r. Fig. 3 shows that the I_D decreases quickly with the increase of r from 10^5 ohm to 10^9 ohm.

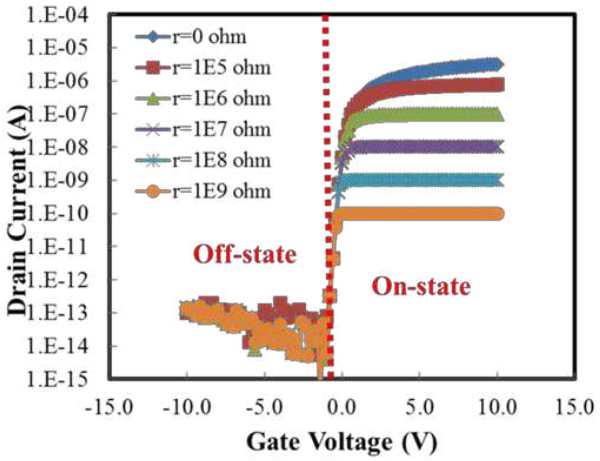

Fig. 3. V_G - I_D curves of a poly-Si TFT attached with a resistor of various resistances.

Since the TFT operation is dependent on the magnitude of the V_G and that of the V_D, the change of the current passing through the attached resistor, i.e., I_D, with respect to the voltage applied to the resistor, i.e., V_D', needs to be investigated. The actual V_D reaching the TFT is smaller than V_D', as shown in the following equations:

$$I_D = \frac{V_D}{R_{eq}} = \frac{V_D' - V_D}{r} \quad (6)$$

or

$$V_D' = I_D * r + V_D \quad (7)$$

Figure 4 shows the V_D vs. V_D' curves of a poly-Si TFT in the Fig. 3 structure. The V_G is fixed at 6V and the resistance of the resistor r varies from 10^3 to 10^6 ohm. When r is small, e.g., 10^3 ohm, the voltage drop through the resistor is negligible. A large current will pass through the resistor. However, when r is large, a large portion of the V_D' is lost to the resistor. For example, at r =10^5 ohm and V_D' = 18V, only a small current can pass the resistor due to the 8 V drop through it.

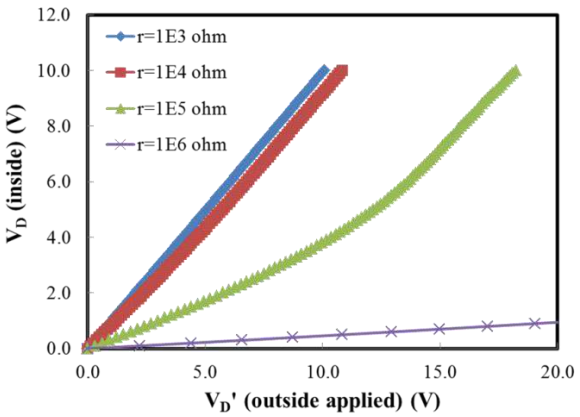

Figure 4 V_D vs. V_D' curve as a function of the resistance of the attached resistor.

Figure 5 shows that the change of I_D with respect to V_D', which is derived from Fig. 4. The resistance r of the attached resistor is critical to the curve. When r is small, the I_D increases with V_D' first and then approaches a saturation value. It is similar to the curve of a typical TFT. As r increases, it is more difficult to achieve the saturation I_D because the magnitude of the voltage applied to the TFT is reduced. At the very large r, e.g., 10^6 ohm, most of the externally applied voltage is lost before reaching the drain electrode of the TFT. Therefore, the I_D cannot reach the saturation value within this operation range.

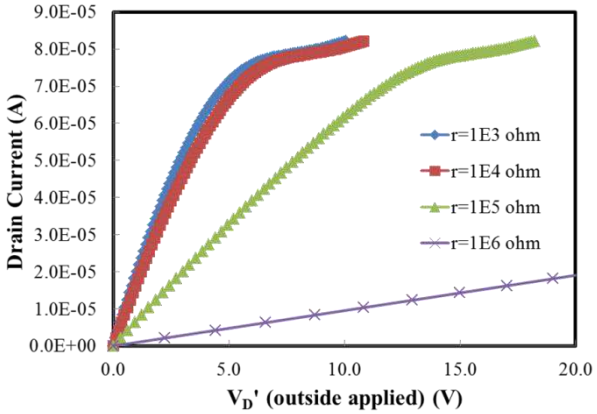

Figure 5 I_D vs. V_D' curve as a function of the resistance of the attached resistor.

Following above discussions, the relationship between the resistance of the attached resistor r and the drain voltage actually reaching the TFT V_D can be calculated. Figure 6(a) shows the V_D vs. r curves of systems at V_D' = 10V with the resistors attached to a-Si:H, poly-Si, and IGZO TFTs, separately. In order to keep the same value of V_G - V_{TH} = 8.5V, V_G = 10 V was applied to the a-Si:H and IGZO TFTs and V_G = 9 V was applied to the poly-Si TFT. In all cases, when r is small, V_D remains close to V_D'; when r is very large, V_D is almost 0 V. In the high mobility poly-Si TFT system, the transition occurs at a smaller r and a wider range than those in the low mobility a-Si:H TFT system. The maximum available currents for resistors driven by different types of TFTs have been calculated, as shown in in Figure 6(b). For the same resistor, the highest mobility poly-Si TFT provides the largest current. However, the low mobility a-Si:H TFT provides a wider arange of stable current. When r is larger 10^8 ohm, the TFT loses its function in the system. Since the TFT and the resistor are connected in series, the low equivalent resistance R_{eq} of the high mobility TFT occupies a smaller portion of the total resistance than that of the high low mobility. Therefore, the range of the high current I_D is reverse to the mobility of the TFT.

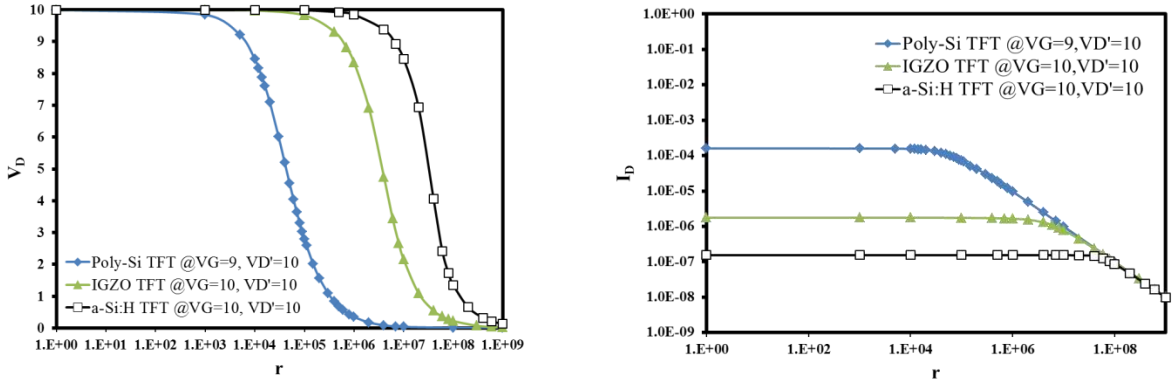

Fig. 6. (a) V_D vs. r and (b) I_D vs. r curves of systems with poly-Si, IGZO, and a-Si:H TFTs.

In addition to the current, the power available for the attached device is important to its function. Figure 7 shows the power available for the device attached to the TFT using the r and the type of TFT as parameters. For each system, with the increase of r, the available power

increases first and then drops. The maximum power is located at the reflection point of the V_D-r curve in Fig. 6(a). If the power required for the attached device is beyond the peak power, it cannot be fully turned on although the complete system can be physically fabricated. For certain applications, such as MEMS or LEDs, the peak power can be a good guideline on selecting the type and size of the TFT, e.g., the mobility and the *W/L* ratio, or the attached device, e.g., the cross-sectional area of the resistor. The design of the system is limited by the dimension, e.g., the size of the attached device, the manufacturability, e.g., the temperature of the process or the substrate size, and the reliability, e.g. the stability of the TFT. In general, the high mobility poly-Si TFT is desirable. However, the low mobility a-Si:H TFT has the advantage of the manufacturability.

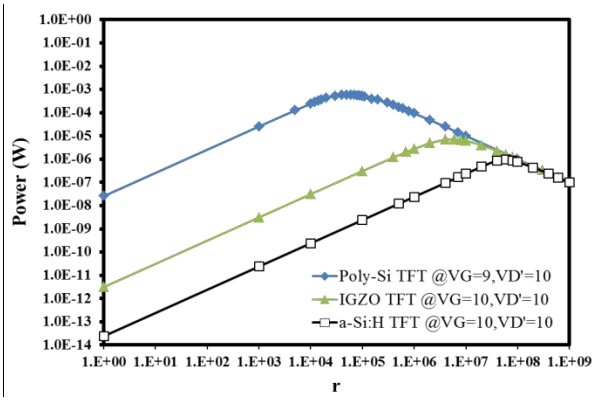

Fig. 7. Powers available to resistors attached to poly-Si, IGZO, and a-Si:H TFTs.

2. Resistor and capacitor attached to the gate electrode of the TFT

For certain applications, more than one device can be attached to a TFT electrode. For example, Figure 8 shows a simplified circuit of a pixel of a touch screen display where a resistor and a capacitor are connected in parallel to the gate electrode of a TFT [17]. Charges can be stored or removed from the capacitor through physical or chemical methods, e.g., mechanical touch or optical exposure. The similar structure can be used for applications such as environmental or biological sensing. The attached resistor or capacitor can change its resistance or capacitance with the variation of the gaseous or aqueous composition.

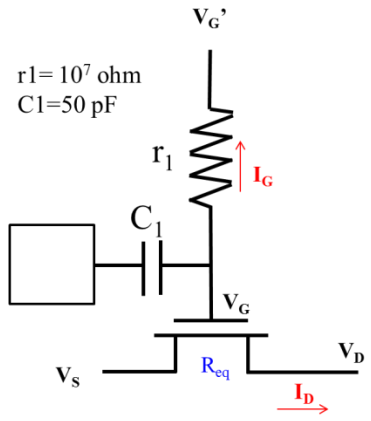

Fig. 8. TFT with a resistor and a capacitor connected in parallel to the gate electrode [17].

The charging and discharging times of the TFT is delayed from the attachment of the resistor and capacitor because of the *RC* delay, as shown below [18]:

$$t = -\log((V_G' - V_G)/V)r1 * C1 \quad (8)$$

where *t* is the time, V_G' is the supply voltage, V_G is the gate voltage, *r1* is the resistance, and *C1* is the capacitance. In the Fig. 8 system, if the *r1* is large, the TFT's response rate will be low, which can affect its function in driving the other device, e.g., attached to the drain electrode not shown in the figure.

Figure 9(a) shows an example of the time required for a poly-Si TFT to reach the on-state with respect to the resistance of the attached resistor, i.e., 10^5, 10^7, and 10^9 ohm, separately, with the fixed *C1* = 50 pF and V_D = 10V. Upon the application of a V_G of 11V, the drain current raises gradually until reaching the saturation I_D. The I_D raise rate is inversely proportional to the resistance of the resistor *r1* according to the *RC* delay principle.

On the other hand, once the capacitor is charged and the TFT reaches the on-state, the V_G' can be removed to drain the storaged charges. There is a time lag before the TFT reaches the off-state. Figure 9(b) shows the influence of the resistance *r1* on the trun off rate of the TFT. The high *r1* makes it difficult to turn off the TFT, which favors the long charge retention in the capacitor. From Figs. 9(a) and (b), a proper *r1* is necessary in order for the TFT to be turned on or off at a specific rate. For certain applications, the *r1* can change with the environment, e.g., light intensity or solution composition. The I_D vs. time curve like that in Fig. 9(b) can be used to monitor the change of the *r1* with the environmental condition. Additionally, the capacitance of the attached capacitor affects the Figs. 9(a) and (b) result, e.g., a large *C1* can slow down the turn on and off rates.

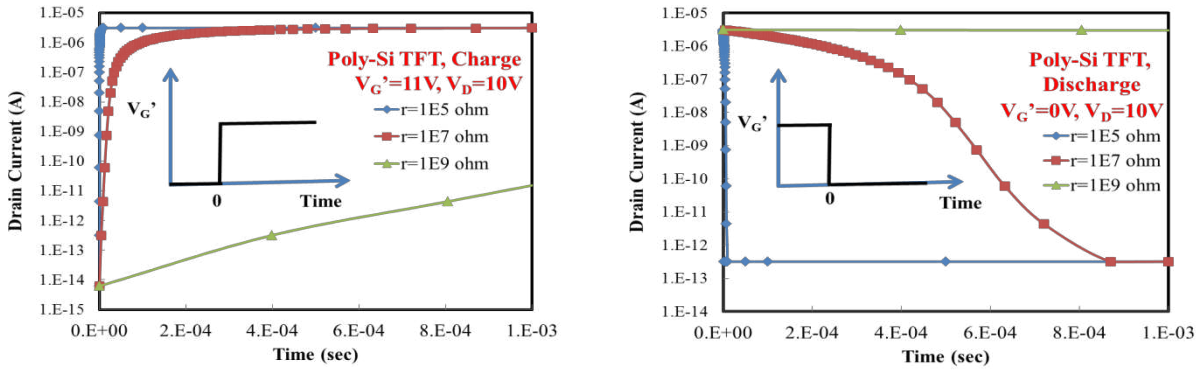

Fig. 9. (a) Raise rate and (b) decay rate of I_D with respect to the resistance of the resistor.

The mobility of the TFT can further influence the I_D's raise and decay rates. Figures 10(a) and (b) show that with the same *C1* = 50 pF, *r1* = 10^7 ohm, and V_D = 10 V, the time to reach the on state increases in the order of poly-Si TFT < IGZO TFT < a-Si:H TFT. However, the time required to drain the stored charges to reach the off state decreases in the order of poly-Si TFT > IGZO TFT > a-Si:H TFT. The poly-Si TFT has the smallest V_{TH} of 0.47 V and the largest mobility among the three TFTs, which makes it easiest to charge the capacitor and to reach the on-state. On the other hand, since all the three TFTs have almost the same V_G decay vs. time curve, the poly-Si TFT needs more time to discharge to reach the < V_{TH} value.

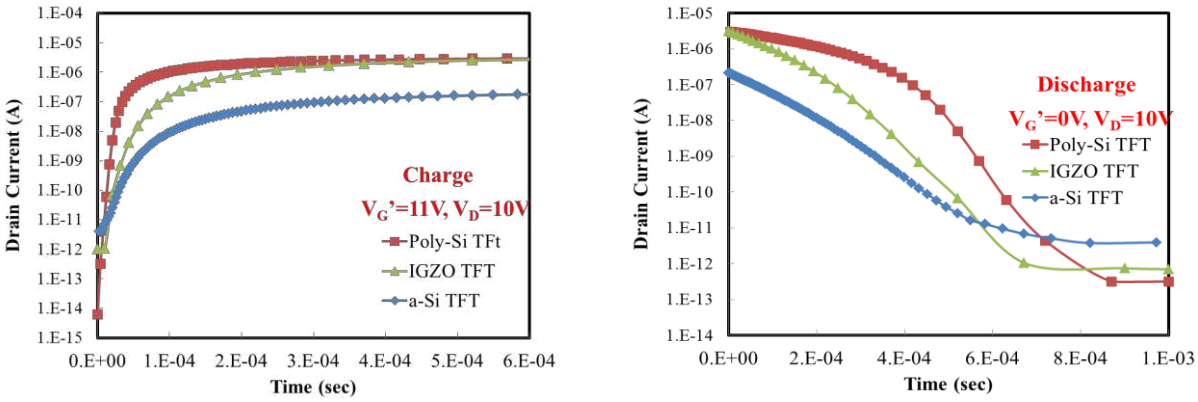

Fig. 10. (a) Raise rate and (b) decay rate of I_D with respect the type of TFT.

Conclusion

Limitations on applying a single TFT to driven a resistor attached to the drain electrode or a capacitor and a capacitor attached to the gate electrode in parallel have been studied. For the former, when a fixed voltage is applied to the attached resistor, the actual drain voltage of the TFT decreases with the increase of the resistance. The magnitude of the current and the size of the power that can be supplied to the resistor decrease with the decrease of the TFT mobility, i.e., in the order of poly-Si TFT > IGZO TFT > a-Si:H TFT. However, when the resistor's resistance is very large, the TFT mobility is not important because the majority of the input power is lost to the resistor. For the latter, the *RC* delay determines the time for the TFT to reach the on- or off-state. When the capacitance of the attached capacitor is fixed, the larger the resistance of the attached resistor is, the longer it takes the TFT to reach the on- or off-state. The high mobility poly-Si TFT can reach the on-state quciker than the low mobility TFT can. However, it takes the longest time to reach the off-state because of the small threshold voltage.

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