Measuring Pulsed/Transient Electrical Properties of OTFTs

Application Note B1500A-13

Introduction

Organic thin film transistors (OTFTs) made of organic or polymeric materials have been developed for applications such as electronic paper and radio frequency identification (RFID) tags due to their ability to be fabricated over a large area such as a flexible plastic printed circuit board.

Unfortunately, the carrier mobility of OTFTs is inferior to the performance levels of existing inorganic materials such as silicon based FETs. This is due to the OTFT's conduction mechanism and the large number of traps at the boundary between the semiconductor and the gate dielectric. To increase the mobility of OTFTs to practical levels, transient response measurements and pulsed bias measurements are essential to understand the carrier transportation mechanisms in detail. In addition, it is also necessary to characterize the OTFT's DC current versus voltage (IV) and capacitance versus voltage (CV) characteristics. A transient response measurement in which current is measured at very short intervals while applying a step voltage is useful to investigate carrier conduction mechanisms and mobility degradation due to trapped charge at the boundary defect. These measurements can be very complicated and may involve fast and large current changes at a step voltage rising edge and a small but relatively slow current change during the falling edge of a step voltage. Also, to understand the IV characteristics in practical situations, such as RF rectifier circuits using OTFTs or logic circuits driven by clock pulses, transient and pulsed IV measurements are necessary.

Until now, transient or pulsed measurement solutions have consisted of user-configured instrument setups, usually consisting of a pulse or function generator, a current to voltage convertor, and an oscilloscope (or voltage sampler). However, these measurement solutions have difficulty producing stable and consistent measurement results. This is mostly due to poorly calibrated components or to the lack of calibration of the entire system. In addition, such measurement solutions constructed from multiple instruments can easily generate measurement errors due to their complicated cabling and the overall error arising from the cumulative errors of the individual instrument components. Therefore, in order to acquire consistent data, an off-the-shelf, self-contained solution with guaranteed specifications is highly desirable.

The B1530A Waveform Generator / Fast Measurement Unit (WGFMU) is an available module for the B1500A Semiconductor Device Analyzer and it can evaluate the pulsed or transient IV characteristics of OTFTs. The WGFMU module can measure current or voltage at sampling rates up to 200 Ms/s and it has up to 16 MHz of bandwidth response. When generating a waveform using its arbitrary linear waveform generator function, the WGFMU module can synthesize waveforms with 10 ns resolution. These features enable the WGFMU to measure the pulsed response of OTFTs in a range that spans down to hundreds of nano-seconds without any additional measurement instruments.

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Organic Thin Film Transistor Development Challenges

The OTFT is a field effect transistor (FET) with a Metal Insulator Semiconductor (MIS) structure. Since the organic semiconductor manufacturing process does not require the high temperatures of its silicon-based inorganic counterpart, OTFTs can be fabricated on substrates made of plastic (please see Figure 1). Also, since both the organic semiconductor and plastic substrate are flexible and light weight, an electrical circuit constructed of them has these attributes as well as superior impact resistance that enable it to be used for electrical paper and RFID tags.

Unfortunately, the carrier mobility of OTFTs is lower than that of conventional silicon-based technologies (please see Table 1). This is due to the OTFT's electron conduction mechanisms and boundary defects between the gate dielectric and substrate.

To expand the usage of OTFTs into a broader range of applications such as the peripheral circuitry in flat panel displays, it is necessary to improve the carrier mobility to a level comparable with that of a poly Si TFT. In order to achieve this goal, further improvements in the manufacturing process, device structure and materials are necessary. These include optimizing the grain size of the organic semiconductor and improving the quality of the boundary between the gate dielectric and organic semiconductor layer. Transient characteristic measurement is the most effective and well-know technique to discern these material and device properties.

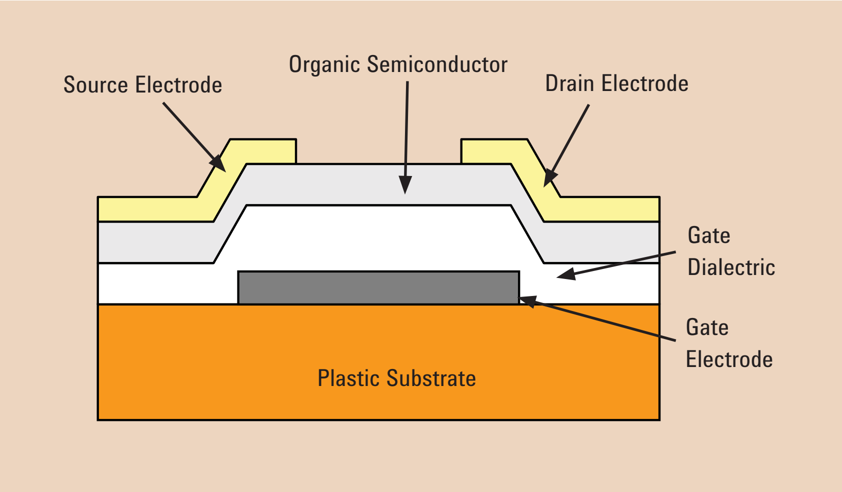

Figure 1. Cross section diagram of Metal Insulator Semiconductor (MIS) OTFT

Table 1. Comparison of mobility of Si and organic semiconductor

Material		Mobility
Si	Mono-crystal	1,000 cm^2/Vs
	Poly-crystal	100 cm^2/Vs
	Amorphous	1 cm^2/Vs
Organic	Low Molecular	~1 cm^2/Vs
	Polymer	~0.1 cm^2/Vs

In addition, when using OTFTs in existing applications it is important to understand the electrical characteristics at operation speed to optimize design of the circuit.

For example, in the case of RFID tags a frequency of either 125 kHz or 13.56 MHz is allowed. Since the RFID tag is powered passively by the RF signal emanating from the RFID tag reader, 13.56 MHz is the preferred frequency due to its shorter antenna and higher power conversion efficiency. At this frequency the FETs used in the RF rectifier circuit (please refer to Figure 2) operate in a non-quasistatic regime during the transient response; this makes it necessary to understand the transient IV characteristics of the rectifier circuit at this frequency.

In the case of logic circuits, estimating the gate propagation delay time is one of most important factors when designing and optimizing circuit operation speed. Unfortunately, the estimated propagation delay based on DC characteristics tends to be slower than the observed propagation delay. This discrepancy is due to carrier mobility degradation caused by charge trapped in the boundary defect, which make circuit optimization difficult. The propagation delay can also be estimated from transient measurements.

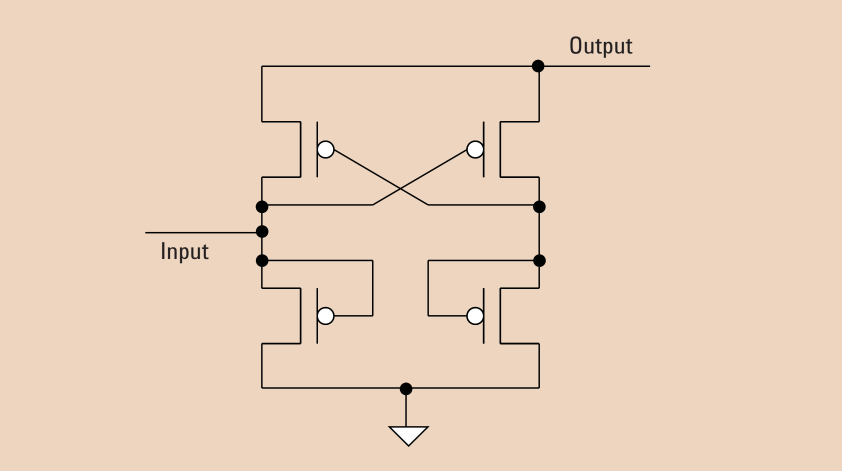

Figure 2. RF rectifier based of OTFT (Rotzoll, R., et al., "Radio frequency rectifiers based on organic thin-film transistors", Applied Physics Letters 88, 123502 (2006)

It is important to understand that the amount of the trapped charge at the boundary defects is determined by the duration of the ON and OFF states because the charge trapped during the ON state is partially released during OFF state. This means that pulsed IV measurement is useful to acquire the IV characteristics of OTFTs at the clock pulse frequencies they would experience in-circuit.

The B1500A's WGFMU module provides an off-the-shelf, self-contained solution for pulsed and transient IV measurement that meets these OTFT measurement challenges.

Pulsed / Transient Response Measurement using the B1500A's WGFMU module

Figure 3 shows a simplified circuit diagram of the WGFMU and Remote Sense Unit (RSU). The WGFMU has arbitrary linear waveform generator (ALWG) voltage generation capability, with the waveform generated by the ALWG output through the RSU. The RSU is where the actual current or voltage measurement is made. The WGFMU has two operation modes: PG mode and Fast IV mode. The PG mode combines a very fast voltage measurement capability with 50 Ohm output impedance to minimize waveform reflections. The Fast IV mode has a slightly slower measurement speed and slower waveform rise/fall times than the PG mode, but it can measure both current and voltage. In fast IV mode five fixed current measurement ranges (from 1 µA to 10 mA) are available, and you can switch between ranges during a measurement.

Using the WGFMU module, a conventional pulsed or transient measurement system (as shown in figure 4) can be significantly simplified (as shown in figure 5).

The conventional system has difficulty producing stable and consistent measurement results due to poorly calibrated, user-created components and to a lack of calibration of the entire system. In addition, measurement solutions constructed from multiple instruments can easily generate measurement errors due to their complicated cabling and the overall error arising from the cumulative errors of the individual instrument components. In contrast, the WGFMU is a single module with guaranteed specifications. By placing the RSU close to the device under test (DUT), the WGFMU's cabling is also kept very short and simple.

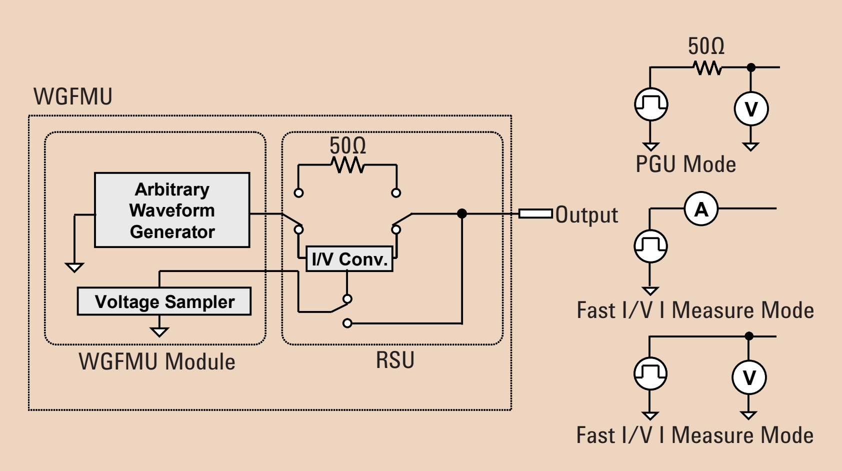

Figure 3. Simplified circuit diagram of the WGFMU module showing its operation modes

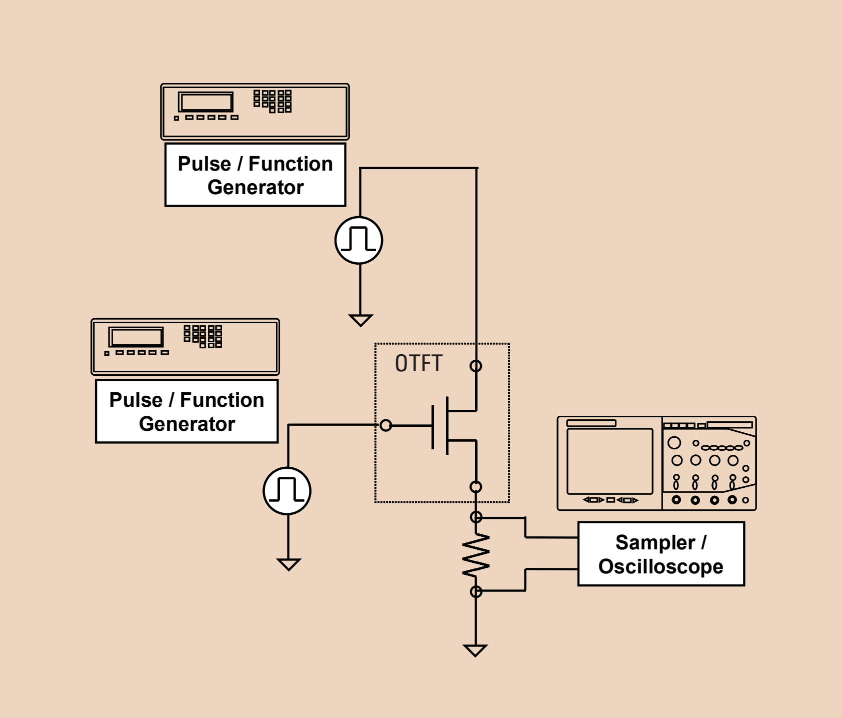

Figure 4. Example of a pulsed/transient measurement system consisting of multiple instruments.

The key features and specifications of the WGFMU module that are relevant to pulsed or transient measurement are described below.
(For more details, please refer the technical data sheet of the B1500A Semiconductor Device Analyzer).

- ALWG Function

The ALWG function of the WGFMU can generate waveforms via as a series of linear segments of variable length (from 10 ns to 10,000 ns with 10 ns resolution). The memory depth of the waveform vector is 2,048, and the WGFMU has a sequence memory that allows it to create an output sequence consisting of up to 512 waveforms. In addition, a burst counter with a burst count of up to 10^{12} is available for each waveforms included in the output sequence that supports the generation of long duration AC signals. These ALWG capabilities allow the WGFMU to generate waveforms with long durations that also include sections with very rapid changes (please see Figure 6).
The WGFMU module supports the following output voltage ranges: ±3V, ±5V, -10 V to 0 V and 0 V to +10 V. The resolution of the output voltage is also very good: 96 μV for the +/- 3 V range and 160 μV for the other ranges; this supports the creation of very precise stimuli that allow you to observe very slight changes in response.

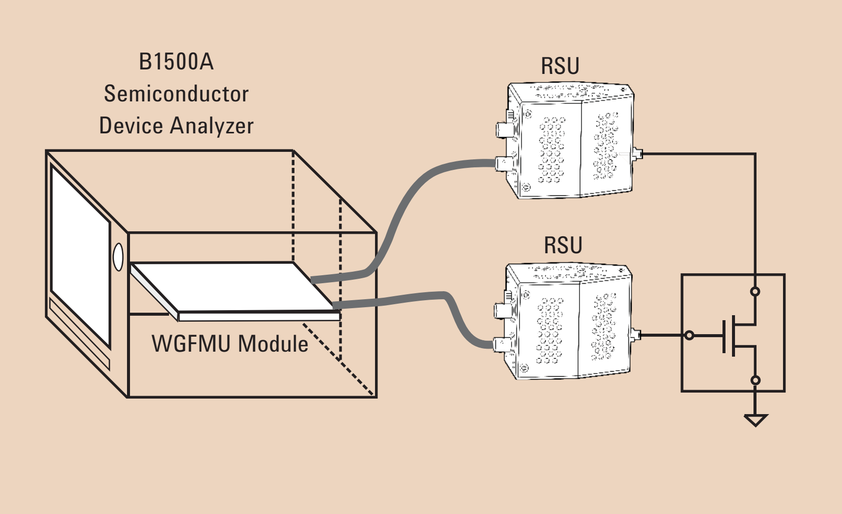

Figure 5. Configuration of pulse/transient measurement system using the WGFMU

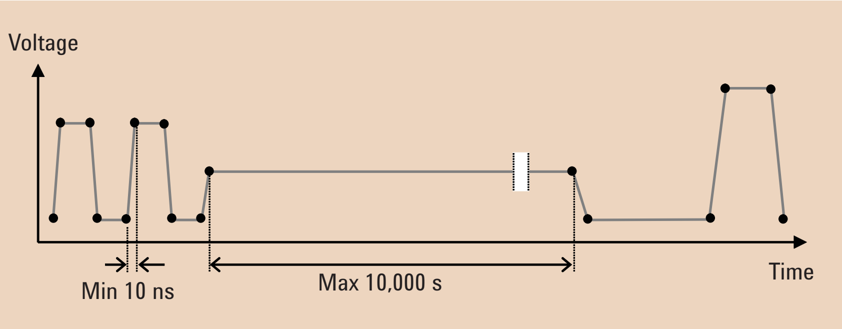

Figure 6. Example showing the variable sampling rate of the ALWG function

The WGFMU can also generate a sequence of pulses using the ALWG function. The minimum pulse rise and fall times and pulse widths depend on several factors, including the output mode, the current measurement range and the load connected to the output of the RSU. Table 2 shows the minimum rise and fall times (defined as the time it takes the pulse to go from 10% to 90% of its initial and final values). By maintaining these rise and fall times, waveform overshoot and distortion are minimized.

For reference, the minimum achievable pulse widths for a 0 V to 5 V programmed pulse with the condition that the pulse be within +/-0.3% of the programmed value.

- Fast Current / Voltage Measurement

In addition to the ALWG function, the WGFMU has a built-in current to voltage (IV) sampling circuit that allows the WGFMU module to measure current or voltage within a very short time interval while simultaneously forcing an arbitrary waveform.
The WGFMU module has five current measurement ranges: 1 µA fixed, 10 µA fixed, 100 µA fixed, 1 mA fixed and 10 mA fixed; these current measurement ranges enable the WGFMU module to cover a wide range of measurement requirements. The measurement resolution is 0.014% of range and the noise floor is 0.2% of range.

The combination of fast and precise current measurement capability and arbitrary waveform generation make it easy to evaluate material properties or to explore new areas of device physics.

To reduce measurement noise the WGFMU has a hardware averaging function; the averaging time can be varied from 10 ns to 20 ms, with 10 ns resolution. Figure 7 shows an example of noise reduction using averaging.

Table 2. Minimum rise time and fall time

Operation Mode	**Current Measurement Range**	**Minimum Rise/Fall Time**			**Load Condition**
		0 to 1V	0 to 5V	0 to 10V	
PG	N/A	30 ns	30 ns	N/A	25 pF, Open
Fast I/V	10 mA	80 ns	80 ns	80 ns	25 pF, 1MΩ
	1 mA	250 ns	250 ns	250 ns	
	100 µA	600 ns	600 ns	1.5 µs	
	10 µA	2 µs	4.5 µs	7 µs	
	1 µA	6 µs	-	-	
		-	35 µs	75 µs	25 pF, Open

Table 3. Minimum pulse width with +/-0.3 % settling (0 V to 5 V)

Operation Mode	**Current Measurement Range**	**Minimum Pulse width**	**Load Condition**
PG	N/A	170 ns	25 pF, open
Fast I/V	10 mA	180 ns	25 pF, 1kΩ
	1 mA	500 ns	25 pF, 10kΩ
	100 µA	1.6 µs	25 pF, 100kΩ
	10 µA	14.5 µs	25 pF, 1MΩ
	1 µA	115 µs	25 pF, 10MΩ

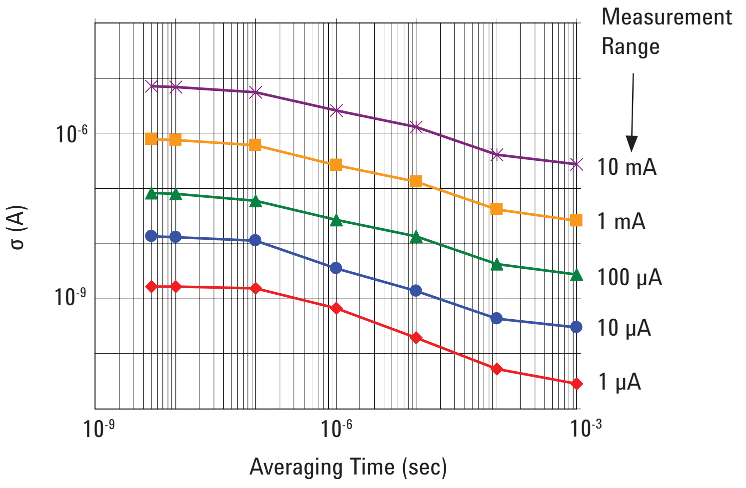

Figure 7. Example of noise reduction by averaging

The minimum measurement sampling rate is from 5 ns or 10 ns to 10,000 s, with a measurement memory depth of approximately 4 million measurement points per channel. In addition, multiple sampling rates can be used within a single waveform. By combining the AWLG function and this unique variable sampling measurement capability, it is possible to observe both rapid and slow responses with a minimum consumption of measurement memory (please see Figure 8).

The WGFMU module can measure both rapid changes at the rising edge of a waveform and small but slow changes on the falling edge of a waveform. This is possible because the WGFMU can execute measurements with a fast sampling rate on the rising edge and a slower sampling rate on the falling edge of a step voltage. Moreover, a slower sampling rate permits a longer averaging time that improves the effective measurement resolution and enables the observation of small changes in current.

Due to its unique combination of ALWG and fast measurement, the WGFMU module can reveal details about the boundary traps (such as energy distribution or time constant) by measuring the current response to step or pulse waveforms with varying output levels, rise and fall times, and frequencies.

In addition, the measurement points can be placed anywhere on the waveform. For example, when performing a pulsed Id-Vg measurement the actual measurement point with reference to the pulse rising edge can be arbitrarily set (please see Figure 9).

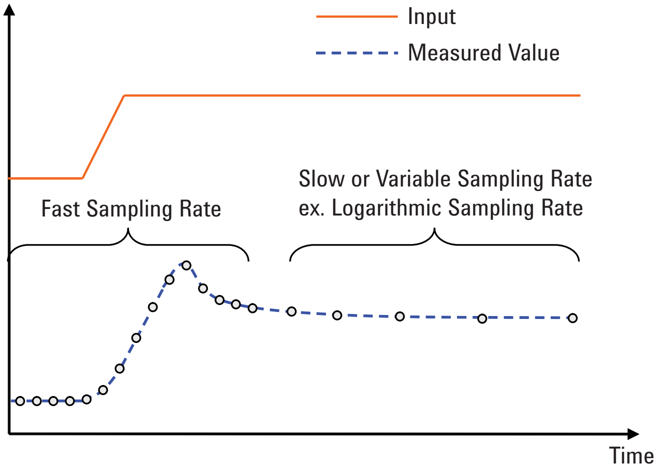

Figure 8. Example showing the variable sampling rate of the sampling measurement

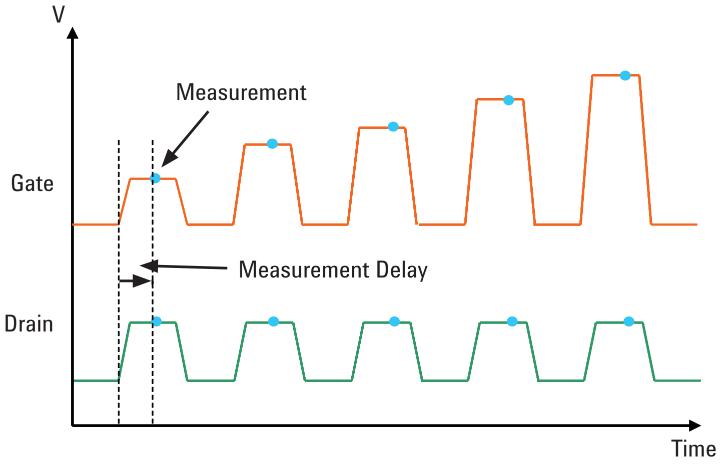

Figure 9. Output sequence of pulsed IV sweep measurement

These features significantly reduce the effort required to extract desired parameters compared to conventional solutions that use an oscilloscope to monitor the current. This is because the oscilloscope technique requires post processing of the captured waveform and it can acquire the waveform with only a single sampling rate. To plot the IV curve, specific points from the captured waveform need to be extracted.

Some important additional considerations for pulsed or transient measurements are the settling time and bandwidth of the measurement equipment, since these determine the achievable minimum pulse width and rise time.

Table 4 shows the current measurement settling time of the WGFMU module. The settling time is defined as the time it takes for the signal to reach 0.3% of its final value.

Table 4. Current measurement settling time

Measurement Range	Settling Time (s)
10 mA	100 ns
1 mA	250 ns
100 μA	1 μs
10 μA	10 μs
1 μA	80 μs

A simple example illustrates these ideas. In the 10 mA measurement range, the settling time (the time required to reach 0.3% of final value) is given by Table 4 as 100 ns. From Table 2 we can see that the minimum rise time in Fast I/V mode for the 10 mA measurement range is 80 ns. Therefore, the minimum wait time is as follows:

$$100\text{ ns} + 80\text{ ns} \times \left(\frac{90\% - 10\%}{100\%} \right) = 200\text{ ns} \cdots (1)$$

This result means that in the case of a pulsed measurement with a 1 μs pulse width, another 800 ns are available for averaging after allowing for the 200 ns wait time. Figure 7 shows that the standard deviation of a current measured with 800 ns of averaging time is around 3 μA. It is also possible to use a lower current range to improve the repeatability of the measured current. For example, in the 1 mA range the settling time is 250 ns and the rise time is 250 ns. This leaves 400 ns for the averaging time, which for the 1 mA range implies a measurement current standard deviation of less than 500 nA. This means that the WGFMU module can measure current with a standard deviation of less than 1 μA for the case of a 1 μs pulse width.

Also, when measuring a gate delay from a step response, measured delay includes additional delay of the measurement circuit. Figure 10 shows the basic ideas of delay determined by bandwidth.

The delay time is determined by the bandwidth of the measurement equipment. Table 5 shows the current measurement bandwidth (-3 dB point) for the WGFMU by measurement range.

The measurement circuit delay time, trs, can be calculated by following equation:

$$\mathrm{trs} = \frac{0.35}{\mathrm{BW}} \quad \cdots(2)$$

Here "BW" is the bandwidth of the measurement equipment as defined the -3 dB attenuation point. The total delay time can be calculated using the following equation:

$$\mathrm{trm} = \sqrt{\mathrm{tri}^2 + \mathrm{trs}^2} \cdots(3)$$

Here tri is the rise time of the input signal, trs is the delay time of the equipment, and trm is the measured delay time. In the case of the 10 mA range, the current measurement bandwidth is around 16 MHz (please see table 5). Using this bandwidth along with equations 2 and 3, additional delay is calculated around 22 ns and the WGFMU is considered to be able to measure the gate delay down to 150 ns with error less than 1%.

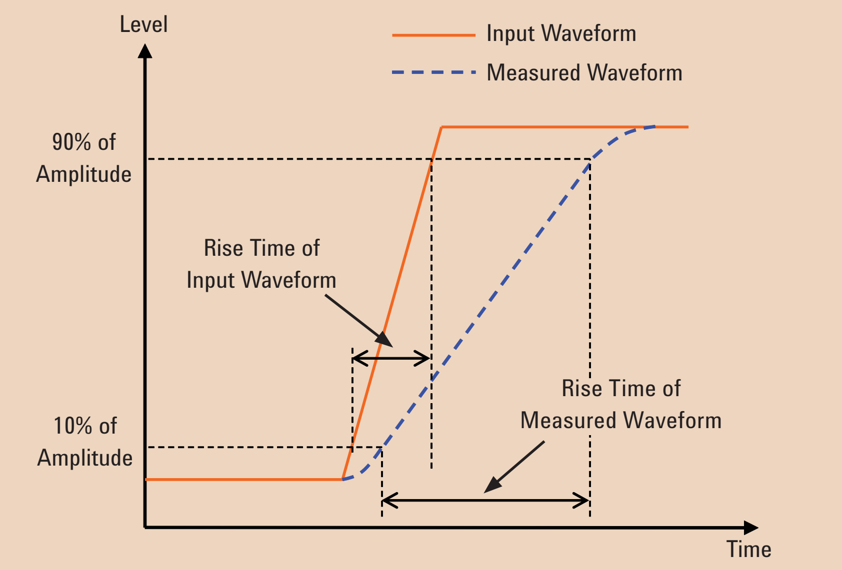

Figure 10. Measurement step response

Table 5. Current measurement bandwidth

Measurement Range	Bandwidth (-3 dB)
10 mA	~16 MHz
1 mA	~8 MHz
100 µA	~2.4 MHz
10 µA	~600 kHz
1 µA	~80 kHz

Versatile Solution for OTFT Characterization

Since OTFTs are a type of the Metal-Insulator-Semiconductor Field Effect Transistor (MIS FET), the leakage current measurement and capacitance-voltage characteristics of the gate dielectric are also important to evaluate its quality. The B1500A Semiconductor Device Analyzer can also perform these types of measurements. The B1500A's supports a variety of source monitor units (SMUs) as well as a multi-frequency capacitance measurement unit (MFCMU). The maximum output range of the SMUs is 200 V/1A (high power SMU) and the minimum measurement resolution of the SMUs is 0.5 μV / 100 aA (high resolution SMU using the atto-sense and switch unit). The MFCMU supports multiple measurement frequencies from 1 kHz to 5 MHz with up to 100 V DC bias. These measurement modules can be installed in the B1500A mainframe along with the WGFMU module, thereby making the B1500A a versatile solution for electrical characterization of OTFTs. In addition, a high voltage semiconductor pulse generator unit (HV-SPGU) is also available, and this module is capable of supplying pulses with +/-40 V amplitude.

B1500A Semiconductor Device Analyzer

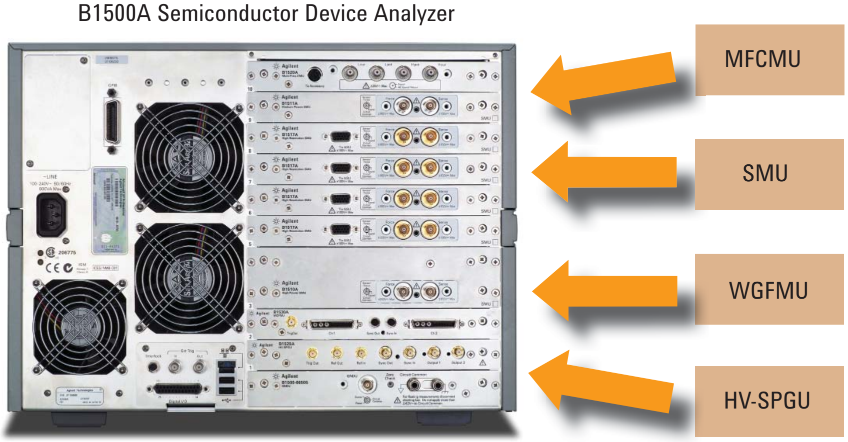

Figure 11. Available modules for B1500A

Conclusion

The organic thin film transistors are considered to be one of the key devices required to realize technologies such as electrical paper or RFID tags.

The B1500A's WGFMU module integrates pulse and function generator capability with current and voltage measurement capability, enabling the B1500A to execute pulsed and transient IV measurement of OTFTs. In addition, the B1500A supports SMUs for static IV measurement, an MFCMU for CV and Cf measurement, and the SPGU for pulsed measurement at higher voltages.
All of these features make the B1500A a self-contained, off-the-shelf measurement solution for the electrical evaluation of OTFTs.

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