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DC Production Testing of OLED Displays

Introduction

Organic Light-Emitting Diode (OLED) displays employ an emerging flat panel technology. Layers of certain organic materials form a p-n junction that emits light when injected carriers recombine. In an OLED display, individual OLEDs form pixels, which are combined in a row and column matrix configuration. An OLED may be monochrome (black or white) or a stacked OLED, which generates more than one color. A typical color OLED display is made up of RGB (red, green, blue) pixels. Displays may employ either active or passive addressing schemes (both not both) to illuminate the pixels. Passive addressing, illustrated in ***Figure 1***, is both less complex and less costly than active addressing and is the most common method used in small displays.

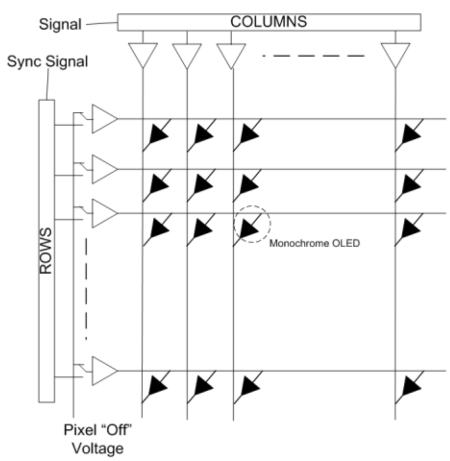

Figure 1. Schematic representation of a passive matrix OLED (PMOLED) display

During R&D and production, electrical characterization of a display may include testing the I-V performance of the OLED(s), reverse bias leakage current, and open/short testing of individual display pixels. An OLED's I-V characteristic roughly approximates a diode. However, an OLED also has different characteristics due to the disordered nature of the materials and much lower carrier mobilities than highly ordered semiconductors. The resulting formation of space charges produces numerous transient effects, some of which cover multiple orders of magnitude in time. Current hysteresis resulting from the direction and speed of the sweep voltage is also present. These effects must be properly characterized and understood before DC test results can be correlated with the quality of the display.

This application note details several cost-effective systems for DC testing of passive matrix OLED displays. These systems provide the accuracy and high volume throughput required for today's production test requirements.

Test Descriptions

Several electrical specifications are important to the performance of OLEDs and OLED displays:

- Reverse bias leakage current
- Swept forward and reverse bias I-V characteristics
- Short and open testing of display pixels

Each of these tests will first be discussed in the context of measuring an individual pixel. By using electrical switching, the tests can then be scaled up for multi-pixel displays of various sizes.

Reverse Bias Leakage Current

The choice of test equipment, cabling, and fixturing for reverse bias leakage measurements is dictated by the magnitude of the leakage current and the desired measurement accuracy. The leakage current is simply the current through the device at a specified reverse bias voltage. As such, the test system must be able to source a stable voltage across the device and measure the relatively small current flow accurately. For some products, a leakage current that's less than a predetermined threshold, (e.g., several tens of nanoamps) may serve as a substitute for an acceptable product. In this case, a simple go/no-go test with a Model 2400 SourceMeter instrument, which provides current measurement accuracy of 10^{-8}–10^{-9}A, is adequate. It's possible to measure currents as low as 10^{-14}A if an electrometer with a voltage source, a properly guarded fixture, and triax cabling are used. ***Figure 2*** is a connection schematic that illustrates performing a reverse bias leakage measurement on a single OLED.

Forward and Reverse Bias I-V Characteristics

The configurations described in the "Reverse Bias Leakage Current" section can also be used to make forward and reverse bias voltage sweeps and current measurements. Both the Model 2400 and the Model 6517A contain bipolar voltage sources that are controlled by a microprocessor. This makes it possible to source a series of voltages, measure the corresponding current, and store the measurements in memory until the sweep is

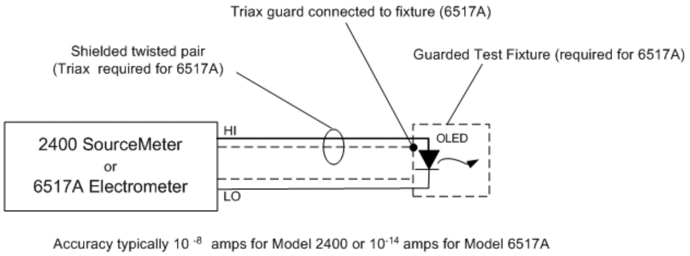

Figure 2. Connection schematic for measuring reverse bias leakage currents of an OLED as low as 10^{-8}A with a Model 2400 SourceMeter instrument or 10^{-14}A with a Model 6517A electrometer.

completed. All the measurements are then downloaded to the PC for post processing.

Display Testing

Testing a display composed of an array of pixels requires automated signal routing to switch the signals from the sources to the pixel(s) under test. A GPIB-controlled switch mainframe such as the Model 7002 is designed to control scanner cards with relays configured as a two-dimensional array. ***Figure 3*** is a schematic representation of how two multiplex scanner cards are connected to a sample display to form a 40×40 matrix. In this example, a single Model 2400 is used, as well as Model 7015-C 1×40 double-pole solid-state multiplexer cards. The Model 7015-C employs solid-state switches with a latency of less than 500 microseconds to ensure maximum test throughput. An offset current of significantly less than 1nA per scanner card allows making accurate leakage current measurements to 10^{-8}–10^{-9}A with the Model 2400. With test systems employing a single SourceMeter instrument, only one pole of each relay, either "HI" or "LO," on the cards connected to the rows and columns is used.

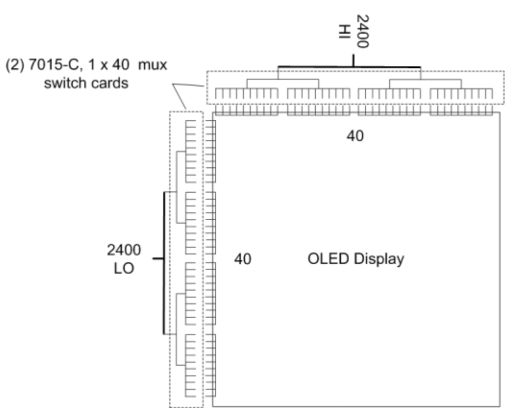

Figure 3. Connection schematic with two 7015-C scanner cards and a 40×40 sample display with a 2400 SourceMeter instrument.

Building a test system with either two or four SourceMeter instruments rather than one ensures higher throughput and more efficient use of switching resources. ***Figures 4a*** and ***4b*** show two and four Model 2400s connected to a display through Model 7015-C 1×40 multiplexer cards. With two or more SourceMeter instruments, both the HI and LO poles on the relays connected to

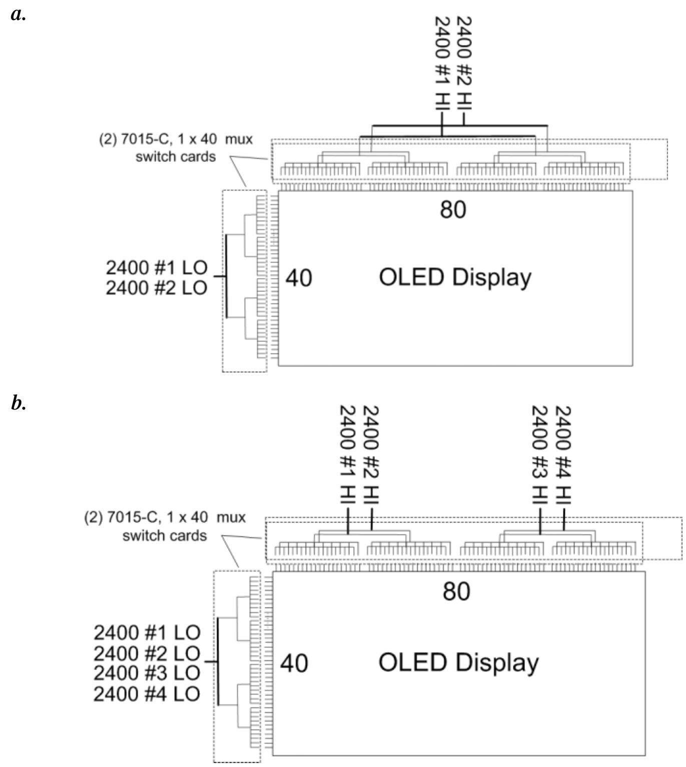

Figure 4. Connection schematic for two Model 7015-C scanner cards and a 40×80 sample display with a) two Model 2400 SourceMeter instruments b) four Model 2400 SourceMeter instruments.

the columns of the display are used. This configuration allows testing two or four pixels simultaneously during each measurement cycle. Each Model 7015-C card contains four banks, "A," "B," "C," and "D," or four individual 1×10 multiplexers with two-pole relays. With two SourceMeter instruments, the HI inputs of four banks are tied together and connected to SourceMeter #1 and the LO inputs of four banks are tied together and connected to SourceMeter #2. For a system with four SourceMeter instruments, the HI inputs of banks A, B are tied together and the LO inputs of banks A, B are tied together. The two 1×20 multiplexers are then connected to SourceMeter #1 and #2. The same connections are made for banks C, D, and SourceMeter instruments #3 and #4.

The number of scanner cards required for an application is determined by the display size, i.e., the number of pixel rows and columns. Using a Model 7015-C card, one scanner card is required per 80 columns and one scanner card per 40 rows. Given that the Model 7002 switch mainframe can hold 10 cards, an additional Model 7002 may be added to the system if more scanner cards are required.

A measurement cycle is defined as the closure of the appropriate relays to route the test signal to the desired pixel(s) and the succeeding source/measurement operation performed by the SourceMeter instrument. The ability to pre-program a scan in instrument firmware reduces the number of SCPI commands sent to each instrument significantly. This minimizes GPIB bus

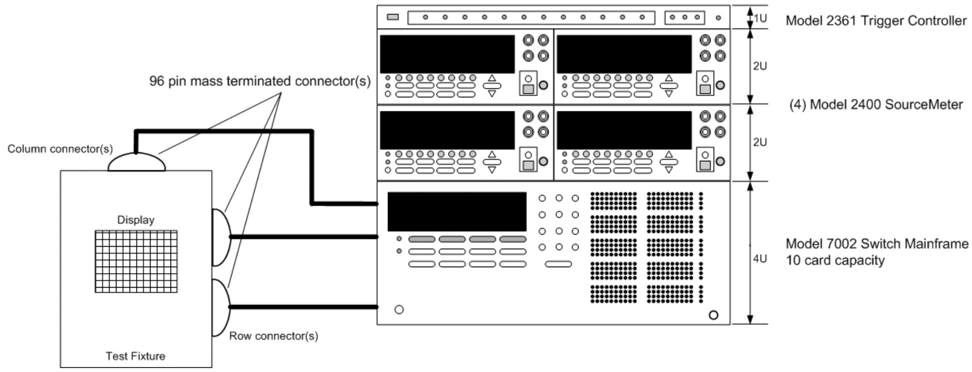

Figure 5. Diagram of the OLED characterization system with Model 7002 Scanner Mainframe, Model 2361 Trigger Controller and four Model 2400 SourceMeter instruments.

traffic, including data transfer, during the test. Binary data formatting reduces the number of bytes transferred per measurement from 17 to four. The Model 2361, a trigger controller with six input/outputs, processes hardware trigger signals that provide high speed synchronization for the source/measure operations of the Model 2400s and switching in the Model 7002. The Model 7011-MTC-2, a specially designed multi-conductor cable, connects the scanner card input/outputs to the test fixture, which is equipped with Model 7011-MTR 96-pin mating connectors. With appropriate software, the scanner mainframe supports leakage current, open/short, and I-V curve analysis on the entire display or an individual pixel. ***Figure 5*** is a schematic representation of a test system with four Model 2400s, a Model 7002, and the Model 2361.

Automated display testing with a current measurement accuracy and resolution of 10^{-12}A requires the use of scanner cards with leakage current ratings of less than 1pA, guarded test fixtures, low noise coax or triax cables, and a high speed electrometer, such as the Model 6517A, rather than the Model 2400. The Model 7158 1×10 multiplexer low current scanner card, with an offset current rating of less than 1pA (<30fA typical), complements the low current measurement performance of the Model 6517A for this application. A 30V operating range ensures that use of the guard circuitry with coax cables does not impose a safety hazard. For applications exceeding 30V, the Model 7058 1×10 multiplexer low current scanner card with triax cables may be substituted for the Model 7158. The Model 7058's relay density per card is 25% of that of the Model 7015-C (1×10 as opposed to 1×40), so additional cards are required to accommodate a display of a given size. In addition, each input on the Model 7158 and 7058 has a single pole or HI terminal surrounded by a guard terminal, as opposed to the double pole HI, LO terminals at each input of the Model 7015. The guarded signal path of the Model 7158 and 7058 cards provides excellent low current performance; however, only one column of the display may be connected to each relay instead of two for the 7015-C card. As a result, one card per ten rows and one card per ten columns are required using the 7158 and 7058 card, which is significantly more than the one card per 40 rows and one card per 80 columns required with the Model 7015-C.

The Model 6517A electrometers are connected with coax cables to Model 7158 cards and with triax cables when using the Model 7058 cards. To form larger arrays, connect the 7158 and 7058 cards with coax or triax cables to form a multiplexer with sufficient fan-out for each side of the display. Connect the input/outputs of the scanner cards to the test fixture with either coax or triax cables. If guarded operation is desired, the appropriate connectors and isolation within the test fixture must be provided. For more information on precision low current measurements and topics such as guarding and the effect of settling time on measurement speed, refer to the current edition of *Low Level Measurements*, published by Keithley Instruments and available free upon request.

Test Fixture Design and Construction

A test fixture was constructed for a 48×64 OLED array to investigate the performance of the OLED test system with four Model 2400's. Traces on the circuit board interface the (3) Model 7011-MTR 96-pin mating connectors, mounted on the edges of the fixture, to contact pads under the jig fabricated from Delrin that contains the display. Three 7011-MTC-2 cables connect the fixture to 7015-C cards in the Model 7002. Silver ZEBRA® elastomeric connectors provide a reliable, stable low resistance connection through the Delrin® jig from the contact pads on the circuit board to the contacts at the edge(s) of the display. After the display is inserted into the fixture and located against the X and Y datum surfaces, four thumb screws are used to attach a bezel securing the display. The depth of the depression in the jig and height of the boss on the bezel are designed to provide adequate, but not excessive pressure to the display contacts on the ZEBRA strips. ***Figure 6*** shows a top view of the complete fixture and ***Figure 7*** provides detail views of the jig mounted on the circuit board.

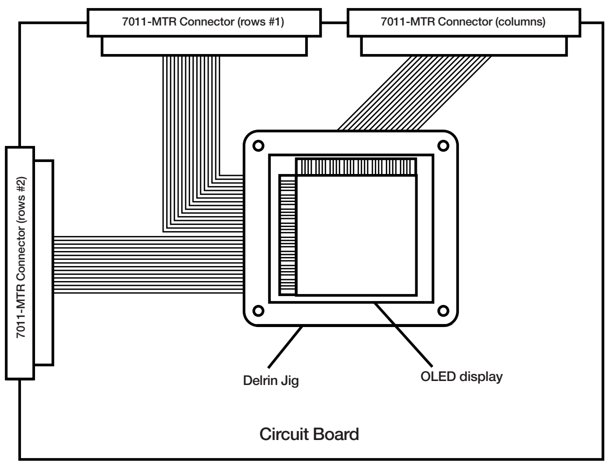

Figure 6. Top view of an OLED test fixture for a 48×64 display

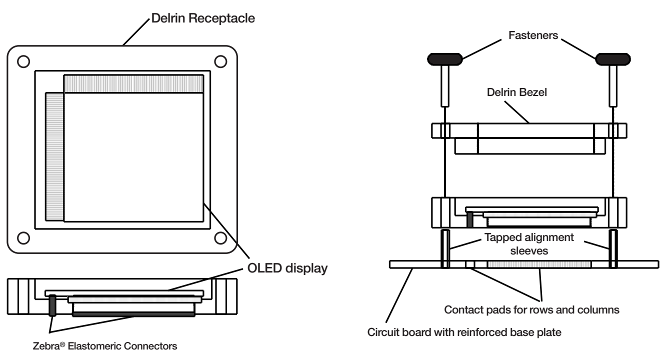

Figure 7. Detail views of the jig designed for a 48×64 OLED display

Sources of Measurement Error

Sources of measurement error are due to the accuracy of the test system and unaccounted-for transients in the OLED during the source/measure operation. During high speed production testing, the ability to perform an accurate DC measurement, under steady-state conditions, is hampered by the need to perform a measurement as quickly as possible. The elapsed time for a test cycle consisting of source/measure and switch operations can vary dramatically. For example, if the Model 2400 is set to operate with the shortest measurement aperture, 0.01 NPLC, the source/measure operation is performed in as little as 1ms. If the integration period or measurement aperture is increased to 1.0 NPLC, the measurement time increases to approximately 17ms. The advantage of increasing the measurement aperture at the expense of measurement speed is superior noise rejection, i.e., quieter measurements.

For stable, repeatable measurements, it is critical that the measured parameter reaches and maintains a steady state value during the source/measure operation. This concept is especially important in testing OLEDs. OLEDs' electrical and optical characteristics are time dependent and exhibit hysteresis effects[1, 2]. Their electrical characteristics differ significantly from the more familiar semiconductor-based optoelectronic emitters. For this reason, a complete understanding of the transient behavior of the test parameter is imperative before attempting to design and implement an automated test system. The characterization of transient performance also facilitates development of the test protocol, simplifies analysis of test data, and promotes a level of confidence in the test system. A source delay period, i.e., a variable delay between the time the signal is applied to the OLED and a measurement is performed, may be applied to reduce the effect of transients. ***Figure 8*** shows the leakage current per pixel for four pixels tested simultaneously with the test system for NPLC = 10 and a source delay of 0.0005 to 10 seconds. At least several seconds are required to achieve a steady state leakage current of less than 1nA.

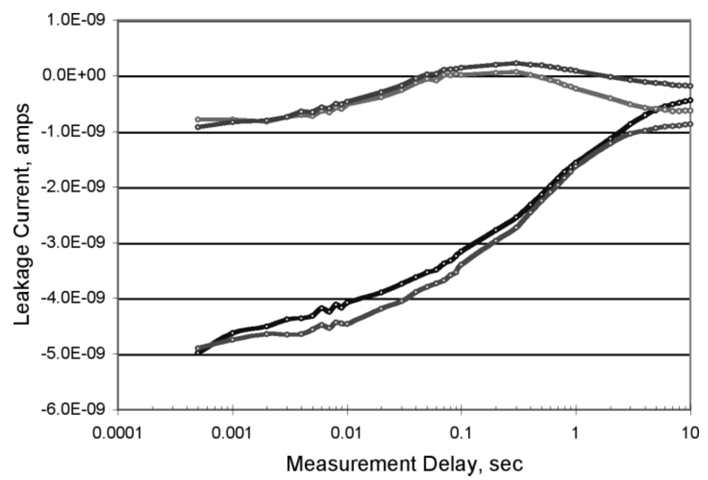

Figure 8. Reverse bias current/pixel for four pixels with a source/measure delay from 0.0005 to 10 seconds with an applied bias of 6V

The measurement performance of the test system depends on the basic accuracy of the test instruments and sources of error introduced by other components of the system. Leakage currents in the cables and switch cards are a source of current measurement error. For the test fixture and cabling, this error increases as the absolute magnitude of the measured current decreases. Selection of the correct scanner card, i.e., rated leakage current at least an order of magnitude less than the lowest measured current, is critical for the application. For the test system designed for measurements of 10^{-8}A using the Model 2400s, guard circuitry is not required.

Voltage measurement errors with a two-wire sense configuration are caused by the "ON" resistance of the relays used on the scanner cards and IR cable losses. When combined, the two relays on the 7015-C cards contribute a maximum <300Ω to the signal path. For current measurements less than 50µA, the voltage error, including typical IR losses, will be small, typically <15µV. For larger currents, such as if an entire column of the display is activated, the error is proportional to the OLED(s) current. This value may be calculated by using $V_{error} = 2 \cdot (R_{relay}) \times I_{oled(s)}$. Applications that require very high voltage measurement accuracy, i.e., the voltage measurement is independent of the DUT current, require a four-wire sense configuration.

The mechanical relays on the Model 7158 and 7058 scanner cards have a contact resistance of approximately 1Ω or less and the voltage error is negligible, even for large currents. The error due to contact potential of the 7015-C, <5mV, and the 7058 and 7158, <250µV and <200µV respectively, may be considered negligible for this application as well.

Test System Measurement Performance

The measurement speed, low current and voltage measurement accuracy of the test system with four Model 2400s was characterized over a wide range of measurement apertures or NPLC settings. The NPLC setting is related to the measurement aperture by

measurement aperture (sec) = 1/60 (NPLC setting)

Figure 9 shows the low current measurement performance the Model 2400 SourceMeter instrument on the 10^{-2}A, 10^{-3}A, 10^{-4}A, 10^{-5}A, and 10^{-6}A ranges for NPLC values from 0.01 to 1.0. The magnitude of the test current is approximately the maximum for each range and each data point represents the standard deviation of 100 measurements. The results indicate for very short integration times, i.e., < 0.1 NPLC, the standard deviation of the current measurements is less than 0.005 % of full scale for the 10^{-2}A, 10^{-3}A, and 10^{-4}A ranges and less than 0.08 % for the 10^{-5}A and 10^{-6}A ranges. A measurement repeatability of ±3σ <2nA is achieved on the 10^{-5}A and 10^{-6}A ranges at the highest measurement rates. ***Figure 10*** shows the results for measurement throughput of a test system with four Model 2400s as a function of integration rate.

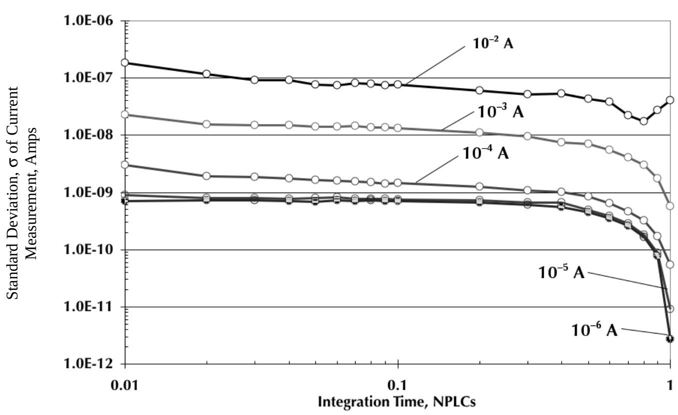

Figure 9. The standard deviation of current measurements vs. NPLCs (integration time) of the 2400 SourceMeter instrument for the 10^{-2}, 10^{-3}, 10^{-4}, 10^{-5}, 10^{-6} measurement ranges

For open and short testing of individual pixels, the Model 2400s are configured as a current source and a voltage measurement is performed. The PC is used to calculate the resistance from the voltage measurements using the source voltage value. This technique reduces the measurement time associated with performing resistance measurements directly with the Model 2400. Measurement accuracy of 0.2% or less may be expected and this level of performance is adequate for go/no-go testing. Test throughput is within several percent of the results for leakage current measurement speed.

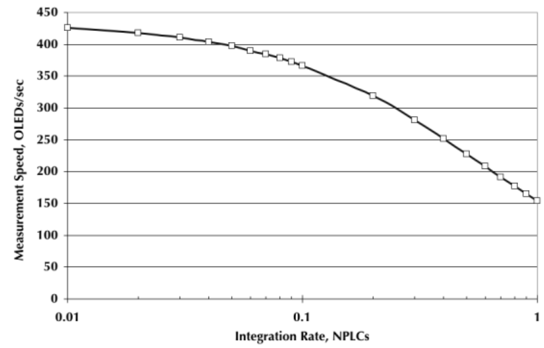

Figure 10. Measurement throughput of the OLED characterization system with four Model 2400s

The use of guarding in the cables, the scanner card, and fixture design drastically reduces leakage currents and supports measuring very low currents possible with the system based on the Model 6517A electrometers and the Model 7158 and 7058 scanner cards. A guarded signal path reduces the long settling times associated with very low current measurements and, in turn, reduces test time. Even with the use of guard circuitry, the Model 6517A's measurement speed is not as fast as the Model 2400's, so its throughput will be lower.

An investigation of the performance of the system with four Model 6517As and ultra low current scanner cards was not performed due the large impact on the performance of the test system by the test fixture and cabling. These components are typically customer supplied and the magnitude of the leakage currents can vary significantly, affecting both the low current performance and measurement settling time.

Display Test Results

To illustrate the results of implementing this test solution, forward current, resistance and reverse bias measurements were made on a 48×64 OLED display with the four SourceMeter test system. The measurement speed was set to 1NPLC (i.e., integration time = 16.7 milliseconds) with a one second source delay. The source delay allows the signal transients to settle before the measurement is performed. ***Figure 11*** shows the results of the pixel resistance measurements for a display considered to be defective. The data confirms almost all the pixels have a relatively high "on" resistance, i.e., >100kΩ. Two pixels have considerably less resistance, one at location row (3) and column (60) that measures approximately 1kΩ, and another at location row (4) and column (37) that measures between 1kΩ and 100kΩ. The actual dynamic resistance may be calculated from

$$R_d = V_{pixel}/I_{pixel}$$

where V_{pixel} and I_{pixel} are the pixel voltage and current respectively. For a 2V bias, the typical pixel current is approximately

20nA, which yields a dynamic resistance of $10^8\Omega$. As a result, the two pixels with a dynamic resistance between 1kΩ and 100kΩ appear to be defective.

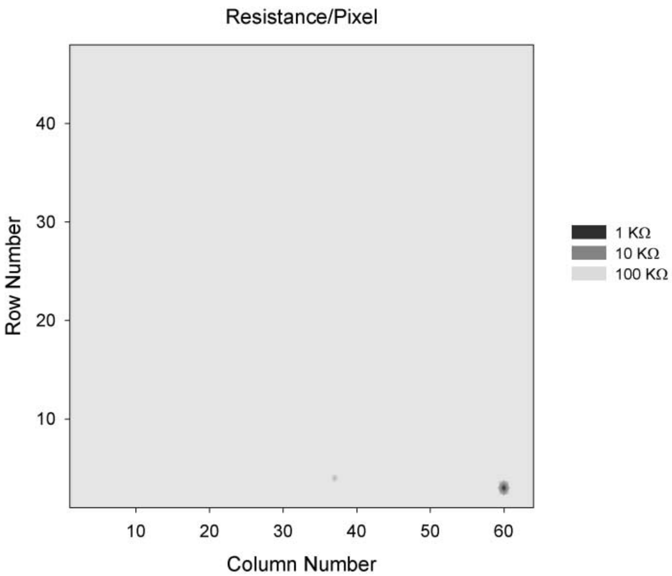

Figure 11. Resistance/pixel with an applied bias of V_{bias} = 2V

Figure 12 shows the forward current consumption/pixel of a different display for V_{bias} = 6V. Almost all pixels show a forward current consumption of approximately 11–13µA. A forward current compliance or protection level of 1mA set at the Model 2400 SourceMeter instrument prevents excessive current flow and potential damage to the display.

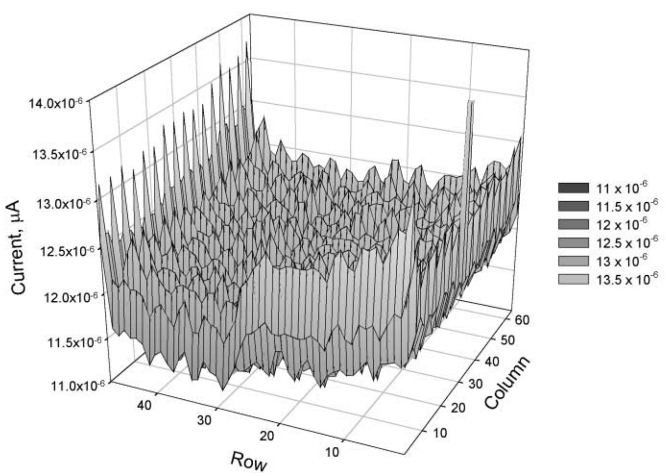

Figure 12. Current consumption/pixel with an applied bias of V_{bias} = 6V

To measure the residual measurement error of the leakage current of the test system at each signal path, a sheet of glass with dimensions identical to the OLED display is inserted into the test fixture. A scan is performed with an applied bias of V_{bias} = –6V. ***Figure 13*** illustrates the results of this scan. The combined leakage current of the cables, relays, and test fixture at any pixel location was measured to be less than 80pA. The "zero offset" error, i.e., current offset at 0V bias, for each Model 2400 is accounted for in these measurements.

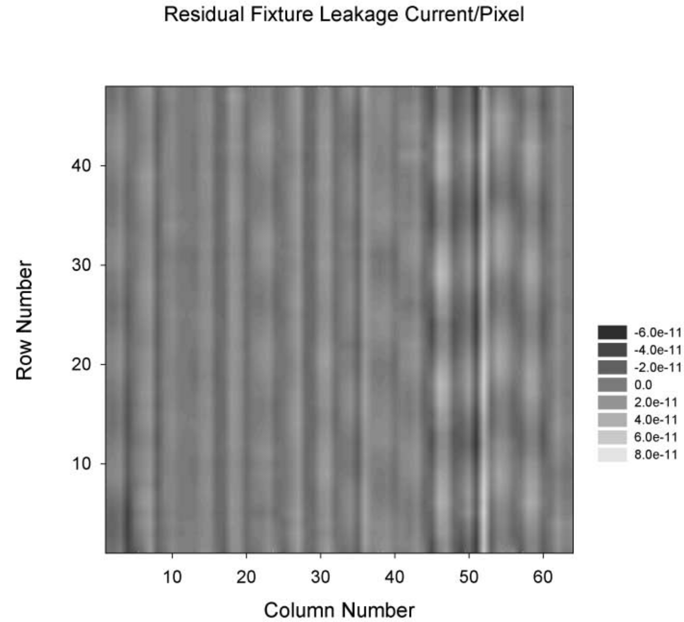

Figure 13. Residual test system leakage current/pixel with an applied bias of V_{bias} = –6V

Figure 14 shows the result of the reverse bias measurement for $V_{reverse}$ = 6V. For this test, taking into consideration the effect of time on the reverse bias leakage current shown in ***Figure 9***, the integration rate was set to 10 NPLC with a source delay time of 15 seconds.

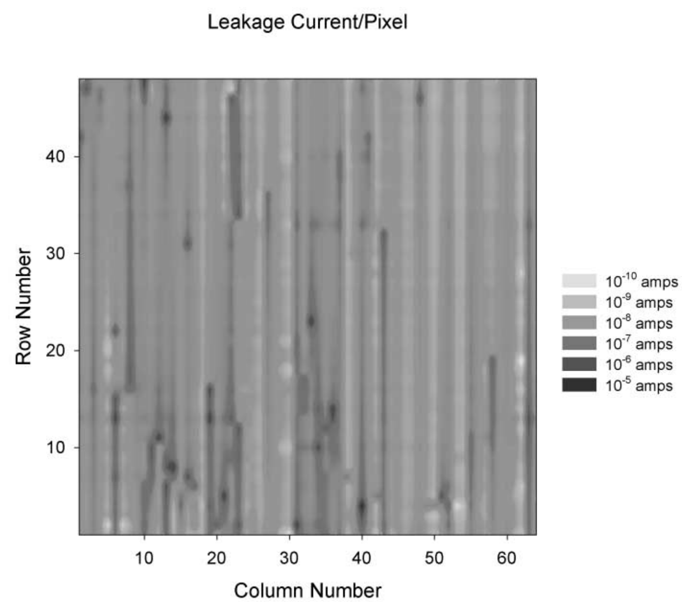

Figure 14. Reverse bias current/pixel for a 48×64 display with $V_{reverse}$ = 6V

Test System Safety

Many electrical test systems or instruments are capable of measuring or sourcing hazardous voltage and power levels. It is also possible, under single fault conditions (e.g., a programming error or an instrument failure), to output hazardous levels even when the system indicates no hazard is present. These high voltage and power levels make it essential to protect operators from any of these hazards at all times. Protection methods include:

- Design test fixtures to prevent operator contact with any hazardous circuit.
- Make sure the device under test is fully enclosed to protect the operator from any flying debris.
- Double insulate all electrical connections that an operator could touch. Double insulation ensures the operator is still protected, even if one insulation layer fails.
- Use high reliability, fail-safe interlock switches to disconnect power sources when a test fixture cover is opened.
- Where possible, use automated handlers so operators do not require access to the inside of the test fixture or have a need to open guards.
- Provide proper training to all users of the system so they understand all potential hazards and know how to protect themselves from injury.

It is the responsibility of the test system designers, integrators, and installers to make sure operator and maintenance personnel protection is in place and effective.

Equipment List

- Model 7002 switch mainframe with 10-card capacity and GPIB control
- Four Model 2400 SourceMeter instruments
- Model 2361 Trigger Controller
- Five Model 8503 DIN-to-BNC Trigger Cables
- Six GPIB cables
- Model 7015-C Solid State 1 x 40 multiplexer cards (1 card per 80 display columns and 1 card per 40 display rows)
- Model 7011-MTC-2 mass terminated cable assemblies (1 per 7015-C card)
- Model 7011-MTR 96-pin Male DIN connectors (1 per 7011-MTC-2)

Example Program

Keithley has developed a demonstration program to operate this system configuration. It is available by accessing Keithley's website at: http://www.keithley.com. Note: The program provided is intended to illustrate the concepts presented in this document. The program may need to be altered to accommodate desired test parameters and timing.

References

1. G. Paasch and S. Drechsler, *"Theory and Simulation of Organic Devices,"* Leibniz Institute for Solid State and Materials Research Dresden, Annual Report, 2000.
2. W. Reiss, H. Riel, T. Beierlein, W. Brutting, P. Muller, and P.F. Seidler, *"Influence of Trapped and Interfacial Charges in Organic Multilayer Light-Emitting Devices,"* IBM J. Res. & Dev., Vol. 45, No. 1, January 2001.

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Vicom Australia

1064 Centre Rd
Oakleigh South Vic
3167 Australia 1300
360 251
info@vicom.com.au
www.vicom.com.au

Vicom New Zealand

Grd Floor, 60 Grafton Road
Auckland 1010
New Zealand
+64 9 379 4596
info@vicom.co.nz
www.vicom.co.nz

KEITHLEY

Keithley Instruments, Inc. 28775 Aurora Road • Cleveland, Ohio 44139 • 440-248-0400 • Fax: 440-248-6168
1-888-KEITHLEY (534-8453) • www.keithley.com

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