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SSD1351 OLED Display Driver Single Event Effects Test Report

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Table of Contents

1. Introduction

The purpose of this test is to serve as a "proof of concept" for *in-situ* monitoring of visual single event effects (SEE) error signatures for small form factor commercial-off-the-shelf (COTS) electronic display boards driver integrated circuits (ICs) at Lawrence-Berkeley National Laboratory's 88-inch cyclotron. The driver IC irradiated during this test was the SSD1351 and is designed to drive a small passive mode organic light emitting diode (OLED) electronic display. The primary SEE concerns for these devices are single event functional interrupts (SEFIs) and destructive SEEs such as single event latch-up (SEL). Testing was focused on identification and compilation of visual error signatures to better understand error rates, and by extension mitigation approaches, for display operating in a SEE environment.

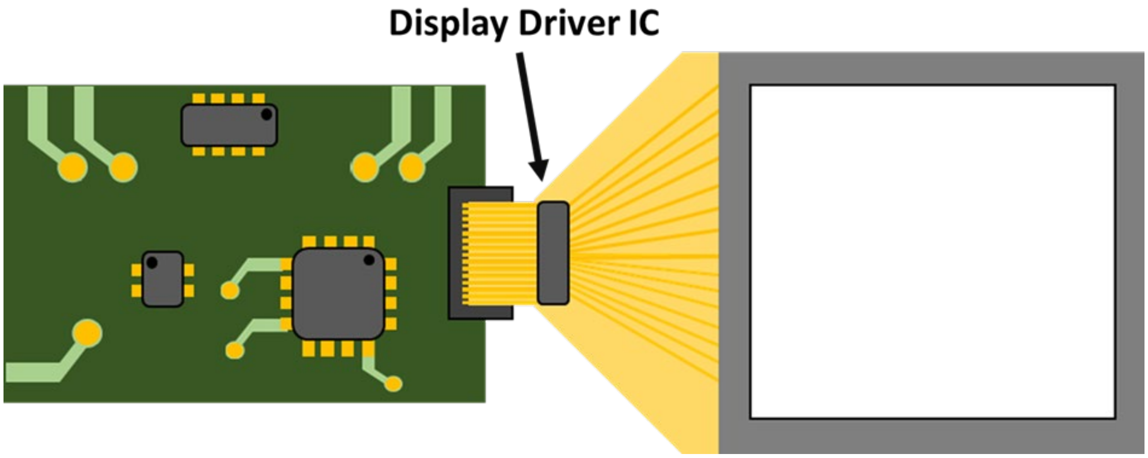

Figure 1: Notional schematic of display boards and the modifications used in this measurement campaign. The screen containing the individual pixels are attached to a electronic board and display driver IC with a flexible tape connector. This allows for "unfolding" the display to access the backside of the display driver IC.

2. Devices Under Test (DUTs)

2.1. Part Background

The OLED display driver used in this test campaign was the 1.5" (128x128 RGB pixel) 16-bit color OLED display board from Adafruit [1] (product ID: 1431) (Fig. 2). This board makes use of a SSD1351 driver IC to drive the display and interfaces with an off-board microcontroller via 4-wire write-only serial peripheral interface (SPI) connection. The SSD1351 is a CMOS OLED/PLED driver with 384 segments and 128 commons output, supporting up to 128RGB x 128 dot matrix display [2]. There is a large variety of functionality contained within the SSD1351, including an RAM required for display control data. Additional power management circuitry for boosting the 5V input voltage to 12V is required for functionality by the OLEDs.

For the purposes of this test, the driver IC is located on the tape connector that connects the light emissive screen and the communicative support circuitry on printed circuit board part of the display. The benefit of this configuration is that the active region can be better accessed from the "backside" of the IC without going through the packaging and additional substrate from the IC die.

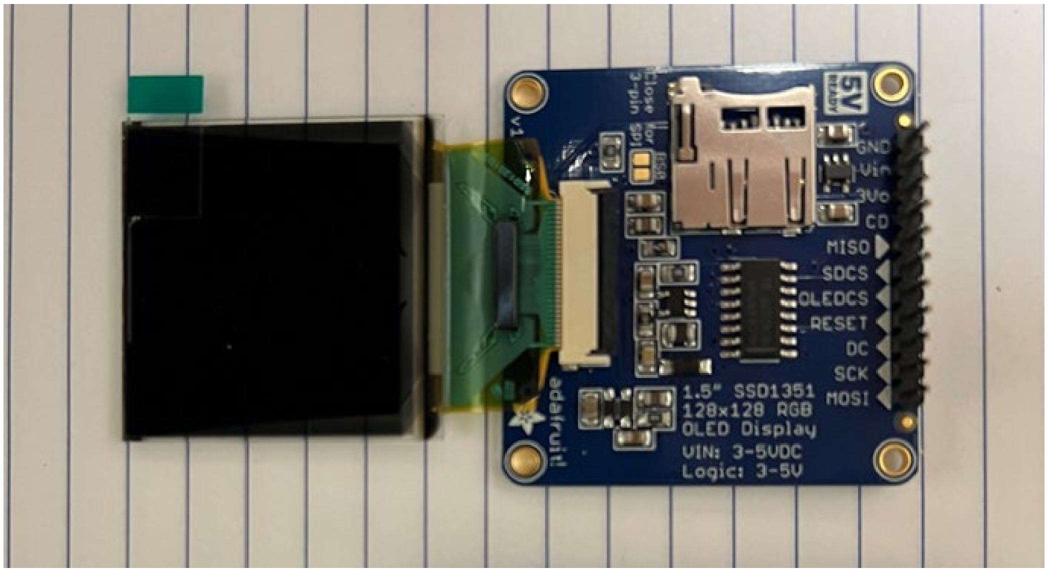

Fig. 2. OLED display board used in these tests.

2.2. Device Under Test (DUT) Information

Each driver IC that is tested is populated on a tape connector of an electronic display board that is intended to drive a small electronic display with control signals provided by a microcontroller via SPI connection protocol. Two (2) display electronic display boards were utilized for these tests. The boards were configured in a "L" configuration such that the "backside" of the driver IC is directly exposed at normal incidence to the ion beam. An added benefit of this approach is that the emissive screen could be monitored at an off-angle via a web camera.

Table 1. Part Identification Information

Part Number	SSD1351
Manufacturer	Soloman Systech
REAG ID	22-045
Quantity Tested	2
Part Function	Electronic Display Driver IC
Part Technology	CMOS
Package	Tape Connector

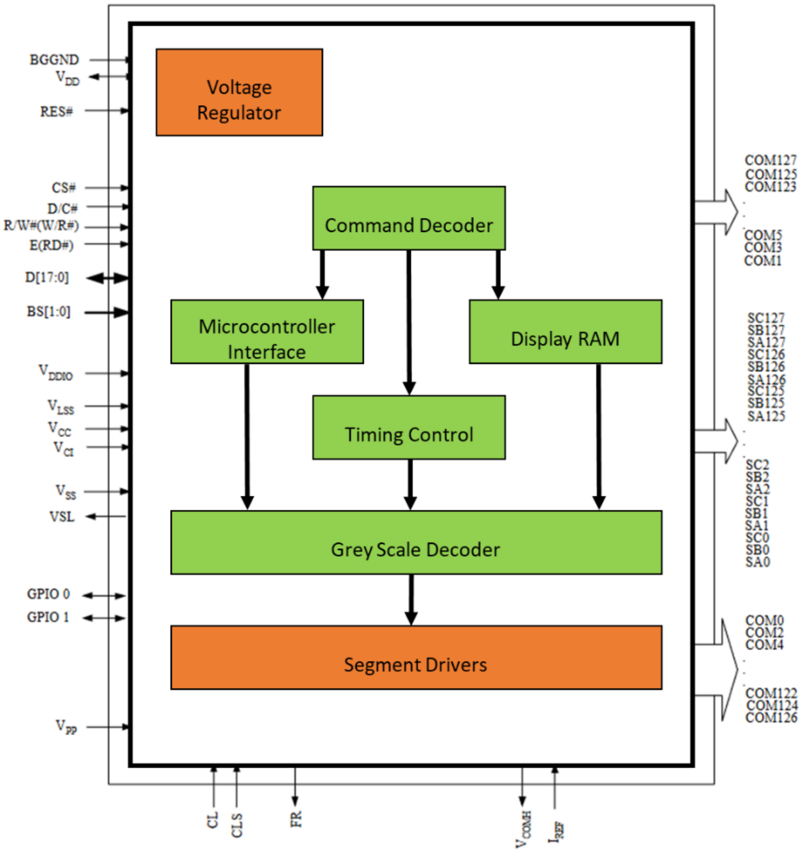

Fig. 3. Functional block diagram of the SSD1351 OLED display driver IC.

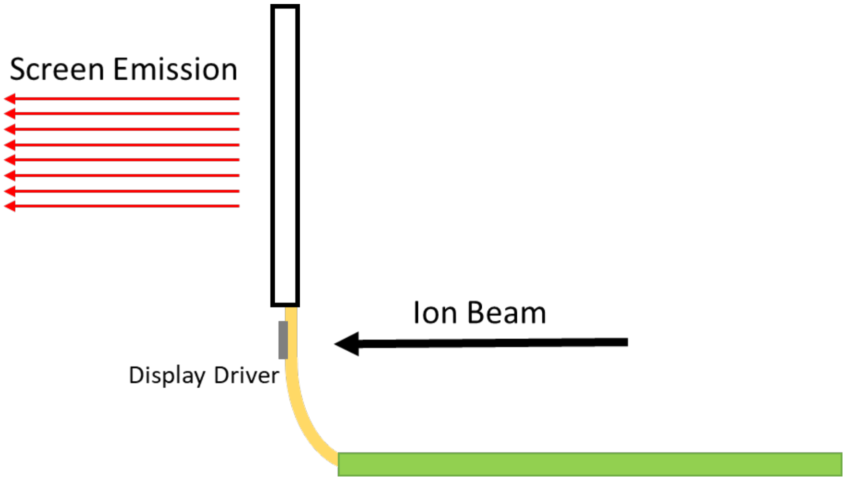

Fig. 4. A picture of the manipulated display board for testing.

3. Test Setup

3.1. Test Facility

Testing was conducted at Lawrence Berkley National Lab's 88" Cyclotron facility using the 16 MeV/amu ion cocktail [3]. Ions were initially selected to maximize particle range through the IC due to concerns about thickness of the die and before increasing the surface LET of the ions. More information can be found in Table 2.

Table 2. Facility Information

Facility	LBNL 88" Cyclotron
Cocktail	16 MeV/amu
Ions	N, O, Cl, Cu, Kr, Xe
Energy (MeV)	234, 277, 540, 1007, 1226, 1955
Angles	0˚, 30˚
Surface Incident LET (MeV·cm^2/mg)	1.2, 1.5, 6.6, 16.5, 25.0, 49.3
In Vacuum (y/n)	No

3.2. Test Conditions and Error Modes

For this test, a power supply with multiple channels were used to provided isolated power to the Arduino microcontroller (providing control signals to the display board) and to input voltage pins of the display board (to power display driver IC, emissive screen, and associated electronics). The benefit of this configuration is that it 1) allows for remote power cycling of each component 2) protects the Arduino from any SEE induced errors propagating from the driver IC and 3) provides current compliance to potentially allow for clearing an SEL high current state with a power reset without irreparably damaging the driver IC or display.

During irradiation, displays were powered on and driven with an Arduino microcontroller (positioned away from the beam to avoid irradiation) to display rotating bars of color as a test image (Fig. 7) for monitoring via USB camera for sustained visual distortion (e.g., sustained line drop out, color shift, loss of display, etc.). It should be noted that all lights available to "user control" were turned off, but red safety lights were required to remain on during irradiation (Fig. 8). This results in some amount of visual distortion in the camera results later within the report. For each beam run, both the Arduino microcontroller and the display board were power cycled to clear any potential latent errors and the driver was irradiated until a sustained SEE signature was observed.

Table 3. Test Conditions

Test Temperature	Room temp
V_{in} to display board	5 V, 250 mA compliance
Test Image	Rotating bars of color
Error Modes	V_{in}, Visual error signatures

Table 4. Test Equipment

Test Equipment	Functionality
Need to Get	Power Supply
Arduino Uno	Microcontroller
Logitech C920	USB camera
Laboratory Computer	Uploading test images to Arduino, monitor USB camera output
Assorted Cabling	Copper cabling, BNCs, USB extenders

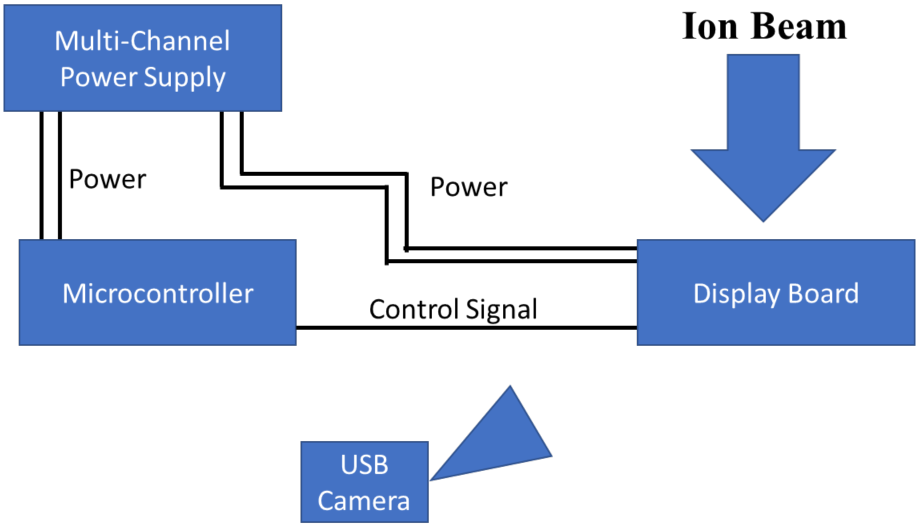

Fig. 5. Block diagram of the test setup. The multi-channel power supply ensures isolation of the power rails of the microcontroller and the display board. Note that the only portion that is irradiated is the display board.

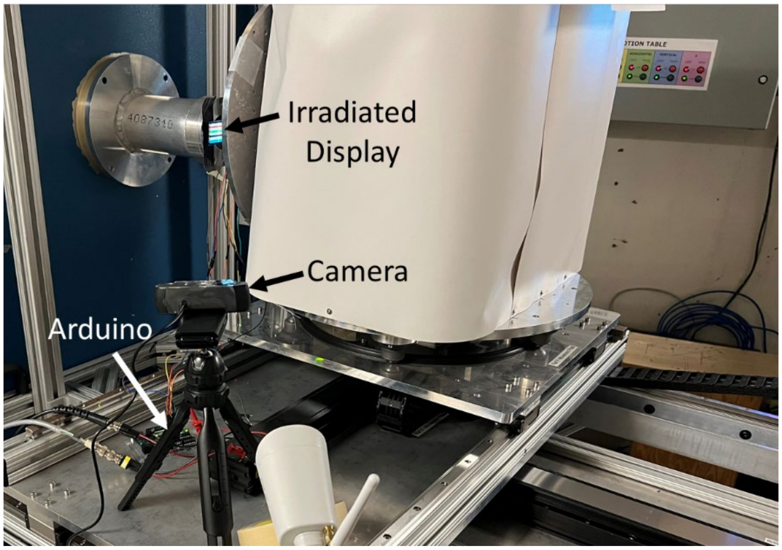

Fig. 6. A picture of the test the setup at the facility. Note the angle and the distance of the camera from the display impacts image quality used to monitor the display during irradiation.

Fig. 7. A pictographic representation of the test image used during irradiation. The color bars slowly scroll across the screen and will wrap around the sides of the screen.

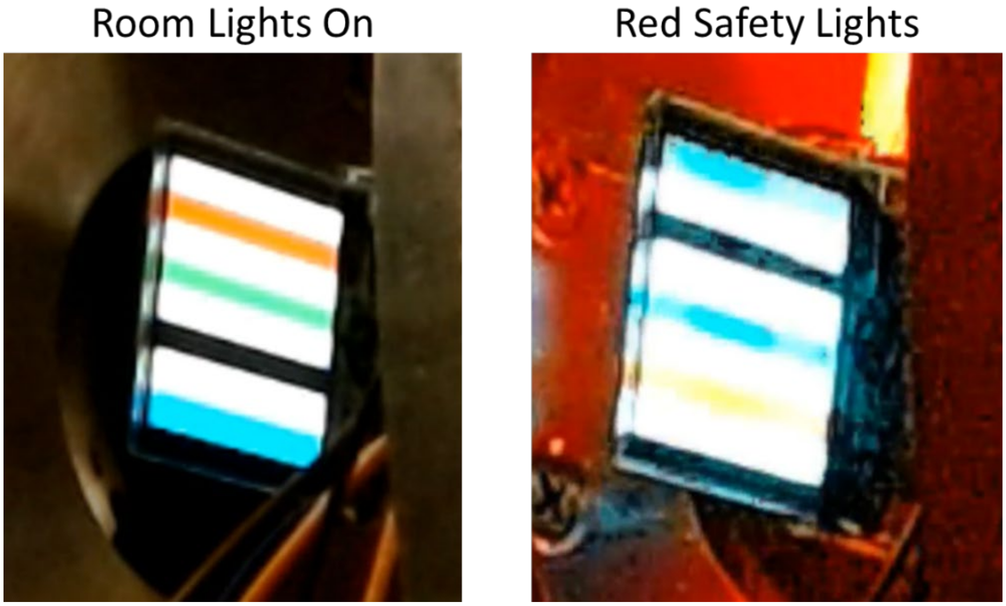

Fig. 8. The red safety lights that must remain on during irradiation impact the image quality and color resolution of the display during irradiation. Note that this degraded image quality will effectively mask some error signatures that similarly degrade display quality.

4. Results

Due to the die thickness unknowns, the initial particle species were selected to maximize the range in silicon as the propensity of COTS memories to SEE susceptibilities implied that with sufficient range SEEs would be observed. During irradiation, temporary visual fluctuations were observed but the display continued to be irradiated until a sustained error signature was observed and a test run was only stopped when a persistent SEFI signature was observed and required a power cycle to clear the state. It should be noted that even at the lowest surface LET there was variety of visual SEE signatures observed during irradiation (Fig. 9 – 10), and with regularity, that would imply the collective onset LET for these errors would be less than the minimum LET used during this these tests.

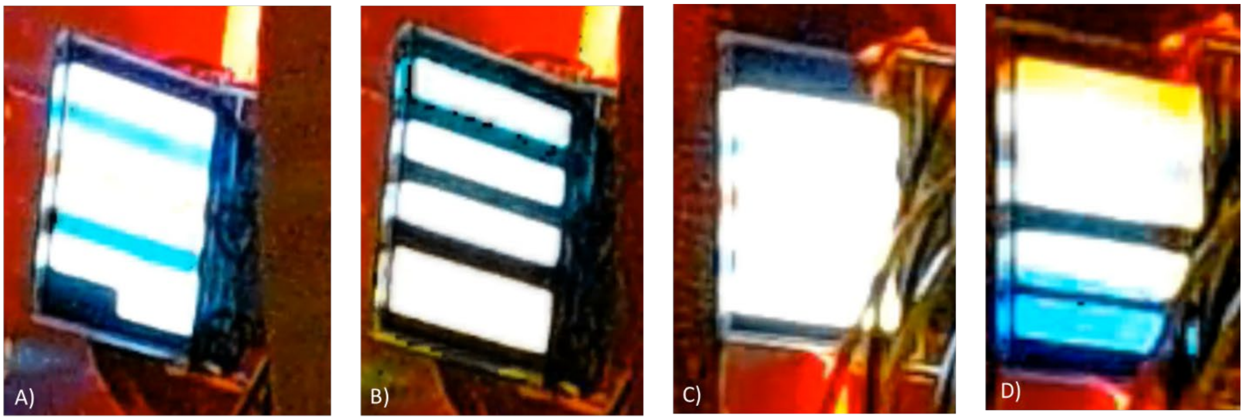

Fig. 9. Examples of visual sustained visual distortions (SEFI) on the displays. A) Loss of control for a subregion of the display. B) Loss of color. C) Loss of clarity due to oversaturation. D) Loss of image integrity.

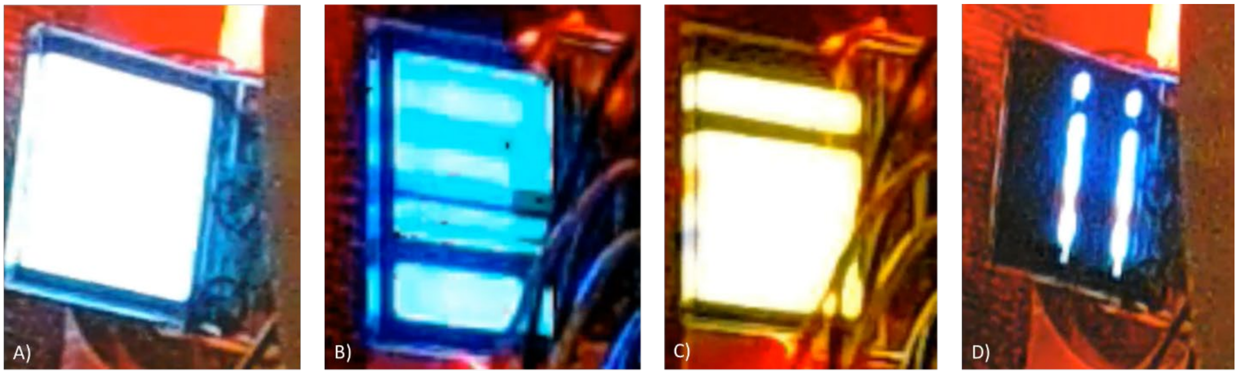

Fig. 10. Additional examples of sustained visual distortions (SEFIs) on the displays. A) Locked to all-white image. B) Loss of image integrity. C) Incorrect control of color mixing with yellow pixels. D) Loss of display for large regions of the display.

4.1. Localization of Error Signatures to Register Locations

Utilizing the manufacturer's "instruction set" intended for interfacing with the driver IC, individual error signatures can potentially be "localized" to a memory register location through a simplified, manual "fault injection" process that reproduces error signatures through command modification. Based on this process, the visual error signatures with the potential memory register location are summarized within Table 5. It should be noted that in practice this could be an SEE-induced bit flip in the register or an error that was eventually written to memory, though commands directly interfacing with configuration bits appear to occur during initialization only and not during nominal operation. With this in mind, correlating errors with register locations allows for potential mitigation of error signatures through modification of display driving software routines to periodically rewrite configuration register during operation. Additionally, this is useful for mitigating a subset (e.g., fixing brightness issues) such that testing and error counts can be better refined to a given error signature.

Table 5. Test Conditions

Error Signature	Command Set
Overall Brightness	Master Contrast Current Control
Changing Color Mixing	Set Contrast Current for Color A, B, C
Inverted Colors	Set Display Mode
Scrolling Direction of Color Bars	Horizontal Scroll
Speed of Scrolling Color Bars	Set Front Clock Divider
Loss of Screen Segment	Set Multiplex Ratio or Set Display Offset
White Screen	Set Display Mode
Black Screen	Set Display Mode or Set Sleep Mode
Static Image	Set Command Lock

5. Summary

"Proof-of-Concept" single event effect measurements were conducted on a COTS electronic device driver intended to drive small form factor passive matrix OLED electronic displays. Displays were reconfigured such that backside of the display drive IC was accessible to the heavy ion beam and could be visually monitored during irradiation using a USB camera to monitor for visual SEFI signatures. These SEFI signatures were catalogued and used to localize the SEFI to a given register/instruction command within the electronic driver IC. It should be noted that these SEFI signatures were identified at rather low LETs, implying protons could have a significant contribution to the error rate. Additionally, one driver was placed into a destructive high current state that persisted through power cycling at a surface LET of 49.3 MeV·cm^2/mg and underscores the necessity of additional heavy ion screening for destructive single events testing prior to operational use.

6. References

[1] Adafruit, "OLED Breakout Board - 16-bit Color 1.5" w/microSD holder," Accessed: Oct. 2022. [Online]. Available: https://www.adafruit.com/product/1431

[2] Solomon Systech, "128 RGB x 128 Dot Matrix OLED/PLED Segment/Common Driver with Controller" Accessed: Oct. 2022. [Online]. Available: https://newhavendisplay.com/content/app_notes/SSD1351.pdf

[3] M. B. Johnson, Heavy Ions, Oct. 2022, [online] Available: https://cyclotron.lbl.gov/base-rad-effects/heavy-ions.