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Degradation model of a linear-mode LED driver & its application in lifetime prediction

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Abstract—Degradations of linear-mode LED driver under different voltage stresses are studied. This driver provides constant current when the output voltage is biased greater than a knee point voltage. During the stress tests, the knee point voltage is found to increase due to the aging of output transistor in the driver[1]. As the knee point voltage exceeds the applied output voltage, the output current cannot be maintained as constant, and the driver is considered as failure. Therefore, the lifetime of the driver can be estimated from the knee point voltage degradation. In this work, a lifetime extrapolation method is proposed based on internal circuit degradation mechanism. Correlations between the degradation model parameters and the applied stress are deduced, and the lifetime of the driver under different voltage stress can be predicted with this correlation.

Index Terms—Circuit reliability, Degradation model, Hot carrier degradation, Lifetime extrapolation

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I. INTRODUCTION

POSSESSING better efficiency and longer lifetime, LED has been widely used in many areas. Some commercial LEDs can promise 150 lm/w and more than 50,000 hours lifetime [2, 3], which is far surpass traditional light sources. LED luminary is expected to replace conventional incandescent and fluorescent light in near future. However, unlike traditional light sources, LEDs cannot be driven directly by 120V or 220V AC power supply, and they must be turned on through drivers which provides a stable output current to the LED, regardless of the voltage applied.

The LED luminary reliability is ensured by having reliable sub-components such as external case, LED chip, electronic driver and so on. Little research work has been conducted to study the reliability of LED driver, among which most of them [4-7] focus on the reliability of individual component like external capacitor, which is used to regulate the output current of switched-mode LED driver. The lifetime of the switched-mode LED driver is estimated based on capacitor degradation. However, the reliability of the driver internal circuit is rarely studied except our previous work [1, 8], where the internal circuit degradation is indeed observed. In [1], it has been proven that the degradation is caused by the aging of the output transistor in the driver and the corresponding failure mechanism is Hot Carrier Injection (HCI). In this work, we will study the impact of HCI on the driver's lifetime.

The hot carrier degradation of MOSFET has been studied by many researchers [9-13]. The degradations are found to be the drift of transistor parameters such as the reduction of transconductance, channel mobility, and the increase in threshold voltage. This degradation follows time dependent power law, and the lifetime is usually estimated based on certain percentage degradation of these parameters [12, 14]. However, this failure criterion for single device is not suitable to study a complex circuit, as certain percentage of parameter drift in single device may have insignificant impact on system performance,

especially for circuit with feedback network. In this work, the correlation between component aging and system degradation will be investigated. The degradation index found in [1] will be used to estimate the lifetime of the driver.

To accelerate the failure, high voltage stress was applied to the driver [1] and the lifetime was found under 13V voltage stress. Inverse Power Law (IPL) is widely used for extrapolation of voltage acceleration[15, 16]. However, the IPL is done by fitting the available lifetime data with corresponding stresses without detailed physical analysis, and this could lead to inaccurate conclusion. In this work, a physical-experimental model is proposed and this method is based on failure mechanism and stress-dependent degradation model parameters.

In this work, correlation between the component aging and system degradation will be interpreted first. The stress test and strength index degradation of the LED driver will be presented next. Based on the strength degradation mechanism, nonlinear mixed effect estimation will be applied to fit the measurement data with the proposed degradation model. After that, the lifetime distribution will be found by using Monte Carlo simulation. Finally, the lifetime will be extrapolated using both IPL and proposed physical-experimental model and their difference will be discussed.

II. CORRELATION BETWEEN TRANSISTOR AGING AND SYSTEM DEGRADATION

A. Device degradation and its impact to circuit reliability

To study circuit reliability, its strength index must be identified. For different circuits, the correlations between the aging of devices in a circuit and the circuit performance are different, especially for circuits with feedback networks. Therefore, this correlation must be clarified in order to identify the health index of the circuit system. To illustrate the concept clearer, two amplifier circuits with their block diagram shown in *Fig. 1* are used as example:

Circuit (a) is a two stage amplifier with gain A_{de1} and A_{de2} . Circuit (b) is an amplifier with feedback network and its open loop gain is A_{de} with feedback factor B_f . The overall gains for circuits (a) and (b) can be expressed as:

$$A_{cir(a)} = A_{de1} \times A_{de2} \quad (1)$$

$$A_{cir(b)} = \frac{A_{de}}{1 + B_f A_{de}} \quad (2)$$

The sensitivity of the circuit degradation due to the aging of its internal device ($A_{de/1/2}$) can be calculated by taking differentiation on both sides of *Eqn.(1)~(2)* and divided by the overall gain A_{cir} of the respective amplifier as follows:

$$\frac{dA_{cir(a)}}{A_{cir(a)}} = \frac{dA_{de1/2}}{A_{de1/2}} \quad (3)$$

$$\frac{dA_{cir(b)}}{A_{cir(b)}} = \frac{1}{1 + A_{de} B_f} \frac{dA_{de}}{A_{de}} \quad (4)$$

where, $\frac{dA_{de(1/2)}}{A_{de(1/2)}}$ is the degradation of the individual component inside the circuit, while

$\frac{dA_{cir(a/b)}}{A_{cir(a/b)}}$ is the degradation of the circuit (system) performance. It can be seen that the

performance degradation for amplifier (a) without feedback network is directly affected by the internal component aging, and the overall gain can be used as the strength index of the amplifier. On the other hand, the amplifier with feedback network is less sensitive to the aging of its internal component and its sensitivity has been reduced by a factor of $\frac{1}{1 + A_{de} B_f}$,

where the value of $(1 + A_{de}B_f)$ can be large. Therefore, the overall gain of the amplifier (b) is insensitive to its component degradation. In this case, the component aging is not correlated to circuit (system) degradation and the circuit reliability is different from its component reliability. Hence, the strength indices for these two amplifiers are different.

B. Driver operational condition and strength characterization

The linear-mode LED driver studied in this work is a commercial product from Macro Block Inc MBI5024. Due to smaller physical dimension and constant robust output current, the linear-mode LED driver is commonly used as driver circuit for LCD back light as shown in *Fig. 2 (a)*. To provide good quality image display, the output current for this driver must be extremely precise and any deterioration of the output current can lead to image defection.

There are 16 output channels for each driver and they behave like current sinks. The LEDs are directly connected to the channels. As discussed in our previous work[8], the driver can be modeled as linear current regulator and the equivalent circuit is shown in *Fig. 2 (b)*. The LEDs are frequently switched on and off for screen refreshing. Thus, both AC and DC stresses are applied to the driver during the operation. The OE pin is used to control the on/off of the output channel. When the OE is at low state, the output channels are turned on and output currents are sinking from the V_{led} to the GND via the LEDs and the output transistors as shown in *Fig. 2(b)~(c)*. In this case, the driver is under DC stress. The DC stress can lead to the aging of the output transistor caused by HCI, and it has been observed and verified in our previous work [1].

The I - V curve of an output channel of the driver is shown in *Fig. 3(a)*. Before the knee point voltage, the output transistor is in triode region and output channel has a finite transconductance expressed as:

$$g_{bef-knee} = \frac{1}{R_{out-bef-knee}} = \frac{1}{\frac{1}{k(V_{dd}-V_{th})} + R_{sense}} \quad (5)$$

where, K is the transistor parameter, V_{th} is the threshold voltage and V_{dd} is the maximum output voltage of the error-amplifier. Since $R_{out-bef-knee}$ is relatively small, the output current is proportional to the output voltage in this region. As the output voltage passes the I - V knee point voltage, the output current is stabilized because the transistor enters into saturation region. After the knee point voltage, the current regulation principle is similar to the cascaded current mirror discussed in [17] and the small signal circuit of the output channel can be drawn as shown in Fig. 3(b). Due to the feedback network, the output impedance is largely enhanced. The transconductance of the output channel is close to zero in this region as given below:

$$g_{aft-knee} = \frac{1}{R_{out-aft-knee}} = \frac{1}{g_m A R_{fb} r_o + R_{fb} + r_o} \approx 0 \quad (6)$$

where, A is the open-loop gain of the amplifier and g_m , r_o are the transconductance and output impedance of the transistor respectively. With $g_{aft-knee} \approx 0$, the output current is independent of the output voltage in this region and it is always regulated to V_{ref}/R_{fb} .

The transconductance $g_{bef-knee}$, $g_{aft-knee}$ and output current after knee point are important parameters to the LED driver as they are related to the driver's DC performance. The $g_{bef-knee}$ is the slope di/dv before the knee point voltage and it was found to decrease with the stress time as observed in [8]. The degradation is due to the drift of transistor parameter k and V_{th} as a result of HCI. Thus, $g_{bef-knee}$ is a good index which indicates the transistor aging. On the other hand, the transconductance $g_{aft-knee}$ and the output current level does not drift with stress time [8], and they are immune to the transistor degradation. The immunity is owing to the use of the feedback circuit, which can provide larger gate voltage to

compensate the transistor degradation. In this case, the $g_{aft-knee}$ and output current level cannot indicate the strength of the circuit. Therefore, the strength index of this driver should be defined related to $g_{bef-knee}$, which is the knee point voltage as shown below [1, 8]:

$$V_{knee} = \frac{I_{out}}{g_{bef-knee}}. \quad (7)$$

III. EXPERIMENTAL RESULTS

As discussed earlier, single device aging cannot be used to predict the system reliability. The system reliability is studied by monitoring the aging of its strength index, which is the knee point voltage for this driver. It has been proven that the weak point of this LED driver is the output transistor and HCI is the corresponding degradation mechanism [1]. Since hot carrier effect is proportional to the lateral electrical field in the channel[9], large output voltage can be applied to accelerate the LED driver degradation.

Test samples are randomly divided into 3 groups, and 9V, 11V and 13V output voltages are applied to these 3 groups respectively. The test condition is summarized in *Table I*.

Unlike the test in [8], the stress test in this work is performed under high voltage at normal temperature of 25°C. No hard failure is observed after 1000 hrs test. The I - V curves are measured using Keithley 2602 periodically to study the knee point voltage degradation. As the degradation mechanism is found to be HCI [1], the degradation rate is fast at the beginning. Due to the shift of peak electrical field and the increase in barrier potential, the degradation rate slows down after the initial period [11, 13, 18]. Therefore, to capture the fast initial degradation, the measurement interval is set more frequently at beginning and then less after the degradation reaches saturation as described below:

1. Every 10 mins ($t < 1$ hour)
2. Every 20 mins ($1 < t < 2$ hour)

3. Every 24 hours ($2 < t < 100$ hours)
4. Every 48~72 hours ($t > 100$ hours)

As Keithley 2602A can only provide discrete raw data of the I - V points, the knee point voltage are extracted for post data processing. Least square method is used repeatedly to fit the linear portion of the I - V curve to estimate its di/dv , which is also the transconductance $g_{bef-knee}$ of the output channel. After that, the knee point voltage is calculated using *Eqn. (7)*.

The knee point voltage degradations for the samples under 9V, 11V and 13V stress are shown in *Fig. 4*. The symbols represent the degradation under different voltage stresses, and the different colors represent the degradation of different units in the same sample sets. The increases of the knee point voltage are observed for these 3 groups, which are proportional to the applied voltage as expected. The self-limiting effect is observed after 24 Hrs test and the degradation follows concave path. The second stage degradation caused by EM in [8] is not observed in this work as the output current is at the rated value (45mA) and the test temperature is much lower. With this current and at room temperature, the possibility of EM is low. It can also be verified by the concave degradation, which is different from the EM degradation [19]. The time-dependent degradation model will be further discussed in the next section.

IV. DEGRADATION MODEL AND LIFETIME ESTIMATION

A. Degradation parameter estimation

As the degradation of knee point voltage is caused by HCI in the output transistor only, its impact on knee point voltage can be expressed using degradation model as shown below[1]:

$$V_{knee}(t, \beta_{1\sim 3}) = \beta_1 t^{\beta_2} + \beta_3 \quad (8)$$

Where, β_1 and β_2 are the degradation parameters and β_3 is the initial value of the knee point voltage. The drift of the knee point voltage ΔV_{knee} can be expressed as:

$$\Delta V_{knee}(t) = V_{knee}(t) - V_{knee}(0) = \beta_1 t^{\beta_2} . \quad (9)$$

As shown in *Fig. 3 (a)*, the driver cannot maintain the intended output current if the knee point voltage exceeds the $V_{out-opt.}$, and hence the lifetime of the LED driver can be determined by the knee point voltage degradation where the failure is defined when $V_{knee} > V_{out-opt.}$

To further confirm the power law relation described in *Eqn. (9)*, $\log(\Delta V_{knee}(t))$ is plotted with stress time $\log(t)$ for the 3 groups as shown in *Fig. 5*. It can be observed that the slope of the knee point voltage degradation reduces after the initial period. This slope reduction is caused by the saturation effect in HCI degradation as discussed earlier. The plot for all these three groups matches the proposed degradation model with different parameters $\beta_{1\sim 3}$, and it further confirms the degradation mechanism as HCI, and that the $V_{knee}(t)$ in *Eqn. (8)* is the actual degradation path for single driver at time t .

In this test, $V_{knee}(t)$ is sampled periodically and the sampled data $y_{knee,ij}$ of unit i at time j can be expressed as:

$$y_{knee,ij} = V_{knee,ij}(t_j, \beta_{1\sim 3i}) + e_{ij} \quad (10)$$

where, $V_{knee,ij}$ represents the actual knee point voltage. e_{ij} is the experimental error that should be normally distributed as $e_{ij} \sim N(0, \sigma_e^2)$. The error distribution will be discussed and

verified using residual analysis. β_{1i}, β_{2i} are the degradation model parameter of unit i . β_{3i} is the corresponding initial knee point voltage value, which is dependent of the process variation. It is expected that $\beta_{1\sim 3i}$ vary from unit to unit and independent of e_{ij} deviation, and can be considered as random variables [15]. These random parameters $\beta_{1\sim 3i}$ are expressed by a mean vector μ_β and covariance matrix Σ_β as shown below:

$$\mu_\beta = \begin{pmatrix} \overline{\beta_{1i}} \\ \overline{\beta_{2i}} \\ \overline{\beta_{3i}} \end{pmatrix} \quad (11)$$

$$\Sigma_\beta = \begin{pmatrix} \sigma_{\beta_{1i}}^2 & 0 & 0 \\ 0 & \sigma_{\beta_{2i}}^2 & 0 \\ 0 & 0 & \sigma_{\beta_{3i}}^2 \end{pmatrix}. \quad (12)$$

The degradation parameters $\beta_{1\sim 3i}$ are estimated by maximizing the marginal likelihood function. This likelihood function is obtained by integrating random coefficient from the joint conditional probability of individual observations, and it is expressed as follow[20]:

$$L(\theta_\beta, \sigma_e^2 | DATA) = \prod_1^n \int_{-\infty}^{\infty} \dots \int_{-\infty}^{\infty} \left[\prod_1^k \frac{1}{\sigma_e} \phi_{nor}(\delta_{ij}) \right] \times f_\beta(\beta_{1i\sim 3i}; \theta_\beta) d\beta_{1i} \dots \beta_{3i} \quad (13)$$

where, $\delta_{ij} = \frac{[y_{ij} - V_{knee,ij}(t_{ij}, \beta_{1i\sim 3i})]}{\sigma_e}$ and $f_\beta(\beta_{1i\sim 3i}; \theta_\beta)$ is the multivariate normal distribution density function. The model parameters are estimated by maximizing the likelihood function of Eqn. (13) with respect $(\mu_\beta, \Sigma_\beta, \sigma_e)$. However, it's impossible to obtain the analytic solution of the multi-integration for Eqn. (13) due to the non-linear degradation model $V_{knee}(t, \beta_{1\sim 3})$ [21, 22]. In this case, non-linear mixed effect (nlme) estimation is used to maximize the likelihood function. The estimation is based on

approximation proposed by Pinheiro [21] that is implemented using `nlmefit` function in Matlab. With `nlmefit` function, the degradation model parameters $\beta_{1i \sim 3i}$ for each chip can therefore be estimated.

With the $\beta_{1i \sim 3i}$ values determined, the degradation path of the degradation model in *Eqn. (8)* can be drawn. The degradation path of the samples with 13V stress is shown in *Fig. 6* for illustration and *No. 1~No. 9* stands for the unit *No.* of the test samples. Some outliers are observed in *Fig. 6(a)*, which can also be detected by the residual normal probability plot shown in *Fig. 6(c)*. As the outlier may bias the estimation of the degradation parameters, it must be removed before the nlme processing. The outlier is removed by eliminating the corresponding observations (circled points in *Fig. 6(a)*) from the experimental data. After the outliers are removed, the nlme is re-applied to the rest of the sampled data. The improved degradation path and residual plot are shown in *Fig. 6(b)* and *Fig. 6(d)*. It can be seen that the residual plot is much better with the outlier removed and it matches the early assumption $e_i \sim N(0, \sigma^2_e)$. Using this method, the parameters $\theta_\beta = (\mu_\beta, \Sigma_\beta)$ for the 3 sample groups are summarized in *Table II*.

B. Lifetime estimation

Based on the estimated parameters θ_β , the knee point voltage degradation under stress conditions can be predicted. As the failure criterion is defined once the knee point voltage exceeds $V_{out-opt.}$, the failure probability can be expressed as a function of $\beta_{1 \sim 3i}$ and $V_{out-opt.}$ value as shown:

$$Pr(T \leq t) = F(t) = Pr[V_{knee}(t, \beta_{1 \sim 3}) \geq V_{out-opt.}]. \quad (14)$$

Thus the lifetime distribution of T depends on the distribution of the parameter $\beta_{1\sim 3}$. For linear degradation, the closed-form of $F(t)$ can be found by substituting parameter distribution into Eqn. (14). However, the analytical solutions does not exist for non-linear degradation model $V_{knee}(t, \beta_{1\sim 3})$ in this work[15] and Monte Carlo simulation is used to estimate $F(t)$.

The Monte Carlo is done by generating large number ($N=10,000$) of pseudo degradation path based on the proposed degradation model and estimated θ_β . The lifetime is estimated by finding the crossing point between the degradation path and the failure criterion $V_{out-opt.}$. The detailed steps of the Monte Carlo method are as below:

- Generate N groups of parameters $\hat{\beta}_{1\sim 3}$ based on the estimated μ_β and covariance Σ_β from the test results.
- Generate N degradation path $\hat{V}_{knee}(t, \hat{\beta}_{1\sim 3})$ based on the estimated $\hat{\beta}_{1\sim 3}$ in step 1
- Compute lifetime $\hat{t}$ of these N degradation path with corresponding failure criterion $V_{out-opt.}$ as shown:

$$\hat{t}_j = \left(\frac{V_{out-opt.} - \beta_{3j}}{\beta_{1j}} \right)^{\frac{1}{\beta_{2j}}} \quad (15)$$

- Evaluate $F(t)$ based on $\hat{t}$ distribution

The error of the Monte Carlo approximation is inversely proportional to N and can be made small by chosen large N value as given below[15].

$$\sqrt{\frac{F(t)(1-F(t))}{N}} \quad (16)$$

The lifetime distribution follows the lognormal distribution as the failure mechanism is HCI, which follows lognormal distribution[23], and they are plotted in *Fig. 7*. One can be seen that the lifetime distributions for the 3 sample groups are almost parallel to each other. The σ for 9V, 11V and 13V groups are 1.08, 1.01 and 1.19 respectively. The difference of σ across these three groups is small and consistent to general random variability. With the estimated σ , it can be concluded that their failure mechanism should be the same[15].

Besides the normal random variability, the unexpected minor environmental/stress fluctuation is also included into the parameter variance Σ_β . Based on the estimated results in **Table II**, the variance of β_1 is negligible and β_3 is the initial knee point voltage, which is independent of the stress environmental/fluctuation. Therefore, this experimental variation majorly affects the variance of β_2 and its impact on lifetime estimation can be expressed as below:

$$\begin{aligned} \Delta \log(\hat{\tau}) = & \log \left(\left(\frac{V_{out-opt.} - \beta_3}{\beta_1} \right)^{\frac{1}{\beta_2}} \right)_{\text{wo-variation}} - \log \left(\left(\frac{V_{out-opt.} - \beta_3}{\beta_1} \right)^{\frac{1}{\Delta\beta_2 + \beta_2}} \right)_{\text{with-variation}} = \\ & \frac{\Delta\beta_2}{\beta_2(\beta_2 + \Delta\beta_2)} \log \left(\frac{V_{out-opt.} - \beta_3}{\beta_1} \right) \end{aligned} \quad (17)$$

where, $\Delta\beta_2$ is due to the experimental variation and $\Delta \log(\hat{\tau})$ is the corresponding lifetime deviation. The lifetime deviation $\Delta \log(\hat{\tau})$ is the unexpected variation and this variation is amplified if a larger $V_{out-opt.}$ is selected. Two degradation curves from 13V group are plotted in *Fig. 8 (a)*. The lifetime deviation $\Delta\tau$ is larger for $V_{out-opt.}=0.83V$ than that of $V_{out-opt.}=0.825V$ as expected. To verify the increased variation due to the selection of larger $V_{out-opt.}$, the lifetime probability plots with different $V_{out-opt.}$ are shown in *Fig. 8 (b)*. The goodness of fit is inversely proportional to the $V_{out-opt.}$ which is the result of larger $\Delta \log(\hat{\tau})$

caused by experimental variation. Therefore, the value of $V_{out-opt.}$ should be cautiously selected to assure the accuracy of lifetime estimation.

C. Lifetime extrapolation

The lifetime estimation in section IV is at high voltage stress and inverse power law is commonly used to extrapolate the lifetime under voltage acceleration[15]as expressed below:

$$\tau(volt) = \left(\frac{volt}{volt_u}\right)^\alpha \tau(volt_u) \quad (18)$$

$$AF(volt) = \left(\frac{\tau(volt_u)}{\tau(volt)}\right) = \left(\frac{volt}{volt_u}\right)^{-\alpha} \quad (19)$$

where, $\tau(volt)$ and $\tau(volt_u)$ are the lifetimes at stress and normal conditions respectively. $AF(volt)$ is the acceleration factor and α is the experimental dependent parameter. As discussed in last section, large $V_{out-opt.}$ can amplify the experimental variation, and it can also increase the unnecessary power consumption and lead to the increase in junction temperature, resulting in various reliability issues [1, 8]. On the other hand, if $V_{out-opt.}$ is set too small and close to the initial knee point voltage, the safety margin (SM), which is given by $SM = ((V_{out-opt.} - \overline{V_{knee}})/\sigma_{knee})$ [24], will be small, and the corresponding reliability is poor since it does not take too long for V_{knee} to increase and exceed $V_{out-opt.}$.

From the lifetime distribution plot in Fig. 8(b), it can be seen that the tail-bend is significant as $V_{out-opt.}$ is greater than 0.825V and a suitable value for $V_{out-opt.}$ in this work is $V_{out-opt.}=0.825V$. With $V_{out-opt.}$ determined, the estimated lifetime vs. stress is plotted in Fig. 9(a). Since the $\log(lifetime)$ has a linear relationship with $\log(volt)$, the inverse power law

is matched. By substituting the estimated lifetime in *Eqn. (19)*, the experimental parameter α is evaluated as $\alpha = -30.8$ and *AF vs. stress level* is plotted in *Fig. 9 (b)*.

As mentioned earlier, inverse power law is based on empirical fit and extrapolation may not be accurate since the slope of acceleration may change when it is extrapolated to lower stress. In this work, physical-experimental model is also proposed. The physical-experimental model is based on the degradation mechanism of the LED driver, which is HCI in the output transistor of the driver [1].

The lifetime of a MOSFET due to hot carrier has been widely discussed by previous researchers and the stress-lifetime correlation has been found[9, 12]. However, the stress-lifetime correlation is normally defined by $(I_{sub}/I_{drain})^n$ vs. lifetime[9] and it cannot be applied to this LED driver as the substrate current is not measurable for commercial packaged IC chip. Moreover, it has been proven in section II that the lifetime of a single device cannot predict the lifetime of a circuit system due to the degradation immunity through feedback network. Thus, the stress-lifetime correlation must be redefined for this driver.

As discussed earlier, the knee point voltage degradation follows power law. This power law relation was derived based on interface-state generation as given [1, 9]:

$$\Delta V_{knee}(t) = I_{out} \times \frac{c \left(\left(\frac{I_{drain}}{W_{eff}} \right) e^{-\frac{\phi_{it}}{q\lambda E_m t}} \right)^n}{\mu_o C_{ox} \left(\frac{W}{L} \right) (V_{dd} - V_{th})} \quad (20)$$

Thus, the degradation model parameters $\beta_{1\sim 2}$ in *Eqn. (9)* can be extracted as shown below:

$$\beta_1 = I_{out} \times \frac{c \left(\left(\frac{I_{out}}{W_{eff}} \right) e^{-\frac{\phi_{it}}{q\lambda E_m t}} \right)^n}{\mu_o C_{ox} \left(\frac{W}{L} \right) (V_{dd} - V_{th})} \quad (21)$$

$$\beta_2 = n \quad (22)$$

Here, C is technology-dependent parameters, E_m is the peak lateral electric field, ϕ_{it} is the barrier height and λ is the electron mean-free path distance[10]. Therefore, it can be seen that the degradation parameter β_1 is proportional to the peak lateral electric field which is related to the applied voltage:

$$\log(\beta_1) \propto -\frac{1}{E_m} \propto -\frac{1}{V_{out}} \quad (23)$$

For parameter β_2 , it is the slope of $\log(\Delta V_{knee}(t))$ vs. stress $\log(t)$. As shown in Eqn. (20)~(22), the value of β_2 for the driver circuit is equivalent the degradation model parameter n for the single transistor[9]. This degradation slope has been reported to vary in a wide range [9, 11, 25]. In this work, the slope of $\log(\Delta V_{knee}(t))$ vs. stress $\log(t)$ is found to be inversely proportional to the applied stress V_{out} and it is consistent to Cham's work[11]. Because both β_1 and β_2 depend on the applied voltage stress, they should be correlated to each other as well. An exponential relation of the degradation parameters for single transistor has been found by Sun[25] and this relation can also be applied to $\beta_{1\sim 2}$ as shown below:

$$\beta_1 \propto \exp(-z\beta_2) \quad (24)$$

To verify the correlation between the degradation model parameters $\beta_{1\sim 2}$ and the applied stress, aging simulation is conducted using Sentaurus TCAD. The circuit for aging simulation is built based on the equivalent circuit shown in Fig. 3. The output MOSFET is defined according to the model in our previous work [1]. The rest of the circuit

components are selected from Sentaurus Compact model. As the degradation mechanism is HCI of the MOSFET in the driver, the "lucky electron model" is applied, the rest of the components are kept virgin during the aging simulation. Thus, the circuit performance degradation is purely due to the aging of the output transistor.

The aging simulation is conducted under different stresses. The device model and stress condition of 13V group is shown in *Fig. 10* for illustration. The knee point voltage of this simulated circuit is retrieved by sweeping I - V , in the same way as we do in the real circuit, and the knee point voltage with aging time is plotted in *Fig. 11*.

Simulation results show that the knee point voltage degradation follows power law, consistent to our test results. To verify the correlation between the degradation model parameters and the stress voltage, $\beta_1 \sim \beta_2$ are extracted and plotted in *Fig. 12*. Based on derived correlation in *Eqn. (23)~(24)*, $\log(\beta_1)$ is plotted with the applied stress $-\frac{1}{V_{out}}$, while β_2 are plotted with $\log(\beta_1)$. The plots of our test results and simulation results are consistent to each other and it matches with our previous analysis. Therefore, the correlation of the stress and degradation model parameter is found and expressed as follows:

$$\log(\beta_1) = c1 \left(\frac{1}{-V_{stress}} \right) + c2 \quad (25)$$

$$\beta_2 = c3 \log(\beta_1) + c4 \quad (26)$$

With the determined correlation, the lifetime under different stressed can be calculated by substituting *Eqn. (25)~(26)* into *Eqn. (15)* as shown:

$$\tau = \left(\frac{V_{out-opt.} - V_{knee}(0)}{\exp\left(c1\left(\frac{1}{-V_{stress}}\right) + c2\right)} \right)^{\frac{1}{c3\left(c1\left(\frac{1}{-V_{stress}}\right) + c2\right) + c4}} \quad (27)$$

here, $C1 \sim 4$ are fitting parameters and they are determined based on the linear regression of the experimental data shown in *Fig. 12* and V_{stress} is the voltage stress. Therefore, the relation between the lifetime and applied stress is found for the proposed physical-experimental model.

The plots of lifetime vs. stress voltage using inverse power law model and our proposed physical-experimental model are shown in *Fig. 13* for comparison, and our measured lifetime can be fitted well by both models. However, the difference in the lifetime estimation from these two models becomes very large when we extrapolate to lower stress. The limitation of inverse power law is that the extrapolation is done based on the available lifetime data only without physical analysis. Thus, the extrapolation of IPL cannot be ensured since the slope of AF may change with the voltage stress, and this could lead to inaccurate conclusion. On the other hand, our proposed physical-experimental model is based on the degradation mechanism of the LED driver. The extrapolation is derived from the correlation between the degradation model parameters and the applied stress. With this correlation, the lifetime of the driver can be estimated through *Eqn. (27)*. For physical-experimental model, the $\log(life)$ and $\log(voltage)$ shows curvature correlation. As the radius of the curvature curve is large, $\log(life)$ and $\log(voltage)$ seems have a linear relation for small range of the voltage and it is the reason that inverse power law can also fit well with the experimental data, as shown in the zoom area of *Fig. 13*.

V. CONCLUSION

In this work, the degradation of a single device and its impact on circuit performance was discussed, and we showed that different circuits may have different immunity to its

internal component degradation. Thus, component degradation cannot be used to predict the reliability of the entire circuit system, and the LED driver circuit studied in this work fall into this category. In this case, health index of the circuit is to be derived, and we have shown that knee point voltage is a good health index for the driver circuit.

Accelerated life test was conducted on the driver circuit under different stress conditions and the lifetime was estimated based on knee point voltage degradation model. Both physical-experimental model and inverse power law model were used for lifetime extrapolation. The limitation of the inverse power law model was shown here due to its lack of physical understanding and its extrapolation is based on available data only. On the other hand, our proposed physical-experimental model was derived from the driver degradation mechanism, and correlations of the degradation model parameters and voltage stress were found and verified by our experimental data and aging simulation. With the degradation model and this correlation, the lifetimes of the LED driver circuit under different stresses were predicted in this work.

REFERENCES

- [1] S. Lan, C. M. Tan, and K. Wu, "Methodology of reliability enhancement for high power LED driver," *Microelectronics Reliability*, no. 0.
- [2] W. D. Van Driel, C. A. Yuan, S. Koh, and G. Q. Zhang, "LED system reliability." pp. 1/5-5/5.
- [3] F. Jiajie, K. C. Yung, and M. Pecht, "Failure modes, mechanisms, and effects analysis for LED backlight systems used in LCD TVs," *2011 Prognostics and System Health Management Conference (PHM-2011 Shenzhen)*. p. MU3157 (5 pp.).

- [4] Z. Yuege, L. Xiang, Y. Xuerong, and Z. Guofu, "A remaining useful life prediction method based on condition monitoring for LED driver," *2012 Proceedings of the IEEE 2012 Prognostics and System Health Management Conference (PHM 2012)*. p. 5 pp.
- [5] S. Bo, K. Sau Wee, C. Yuan, F. Xuejun, and Z. Guoqi, "Accelerated lifetime test for isolated components in linear drivers of high-voltage LED system," *2013 14th International Conference on Thermal, Mechanical and Multi-Physics Simulation and Experiments in Microelectronics and Microsystems (EuroSimE)*. p. 5 pp.
- [6] H. Lei, and N. Narendran, "Developing an accelerated life test method for LED drivers," *Proc. SPIE - Int. Soc. Opt. Eng. (USA)*. p. 742209 (8 pp.).
- [7] L. Han, and N. Narendran, "An Accelerated Test Method for Predicting the Useful Life of an LED Driver," *IEEE Transactions on Power Electronics*, vol. 26, no. 8, pp. 2249-2257, 2011.
- [8] S. Lan, C. M. Tan, and K. Wu, "Reliability study of LED driver – A case study of black box testing," *Microelectronics Reliability*, vol. 52, no. 9-10, pp. 1940-4, 2012.
- [9] H. Chenming, C. T. Simon, H. Fu-Chieh, P. K. Ko, T. Y. Chan, and K. W. Terrill, "Hot-Electron-Induced MOSFET Degradation - Model, Monitor, and Improvement," *Solid-State Circuits, IEEE Journal of*, vol. 20, no. 1, pp. 295-305, 1985.
- [10] J. E. Chung, P.-K. Ko, and C. Hu, "A model for hot-electron-induced MOSFET linear-current degradation based on mobility reduction due to interface-state generation," *IEEE Transactions on Electron Devices*, vol. 38, no. 6, pp. 1362-1370, 1991.
- [11] K. M. Cham, J. Hui, P. Vande Voorde, and H. S. Fu, "SELF-LIMITING BEHAVIOR OF HOT CARRIER DEGRADATION AND ITS IMPLICATION ON THE VALIDITY OF LIFETIME EXTRACTION BY ACCELERATED STRESS," *Annual Proceedings - Reliability Physics (Symposium)*. pp. 191-194.

- [12] D. S. Ang, and C. H. Ling, "Unified model for the self-limiting hot-carrier degradation in LDD n-MOSFET's," *IEEE Transactions on Electron Devices*, vol. 45, no. 1, pp. 149-159, 1998.
- [13] D. S. Ang, and C. H. Ling, "On the time-dependent degradation of LDD n-MOSFETs under hot-carrier stress," *Microelectronics Reliability*, vol. 39, no. 9, pp. 1311-1322, 1999.
- [14] E. Takeda, and N. Suzuki, "EMPIRICAL MODEL FOR DEVICE DEGRADATION DUE TO HOT-CARRIER INJECTION," *Electron device letters*, vol. 4, no. 4, pp. 111-113, 1983.
- [15] W. Q. MEEKER, and L. A. ESCOBAR, *Statistical Methods for Reliability: A wiley-Interscience Publication*, 1998.
- [16] E. A. Elsayed, *Reliability engineering / Elsayed A. Elsayed*: Reading, Mass. : Addison Wesley Longman, c1996., 1996.
- [17] P. R. GRAY, P. J. HURST, S. H. LEWIS, and R. G. MEYER, *analysis and design of analog integrated circuits*, FOURTH EDITION ed.: JOHN WILEY & SONGS, INC., 2001.
- [18] A. Raychaudhuri, M. J. Deen, W. S. Kwan, and M. I. H. King, "Features and mechanisms of the saturating hot-carrier degradation in LDD NMOSFET's," *IEEE Transactions on Electron Devices*, vol. 43, no. 7, pp. 1114-1122, 1996.
- [19] C. M. Tan, and A. Roy, "Electromigration in ULSI interconnects," *Materials Science and Engineering: R: Reports*, vol. 58, no. 1-2, pp. 1-75, 2007.
- [20] R. Pan, and T. Crispin, "A hierarchical modeling approach to accelerated degradation testing data analysis: A case study," *Quality and Reliability Engineering International*, vol. 27, no. 2, pp. 229-237, 2011.

- [21] J. C. Pinheiro, and D. M. Bates, "Approximations to the log-likelihood function in the nonlinear mixed-effects model," *Journal of Computational & Graphical Statistics*, vol. 4, no. 1, pp. 12, 1995.
- [22] L. A. Escobar, and W. Q. Meeker, "A Review of Accelerated Test Models," 2007.
- [23] E. S. Snyder, "The impact of statistics on hot-carrier lifetime estimates of n-channel MOSFETs," *Proc. SPIE - Int. Soc. Opt. Eng. (USA)*. pp. 180-7.
- [24] P. D. T. O'Connor, D. Newton, and R. Bromley, *Practical Reliability Engineering*, Chichester: John Wiley & Sons Ltd, 2002.
- [25] S. W. Sun, M. Orlowski, and K. Y. Fu, "Parameter correlation and modeling of the power-law relationship in MOSFET hot-carrier degradation," *IEEE Electron Device Letters*, vol. 11, no. 7, pp. 297-9, 1990.

Fig. 1. (a) Amplifier circuit without feedback (b) Amplifier circuit with feedback

Fig. 2. (a) The LCD backlight system (b) Equivalent circuit of output channel (c) Signal waveform

Fig. 3. (a) The simulated I-V curves (b) Small signal circuit of the LED driver $V_{out} > V_{knee}$

Fig. 4. knee point voltage degradation

Fig. 5. $\Delta V_{knee}(t)$ vs. t

Fig. 6. (a) Estimated degradation path with outliers (b) Estimated degradation path without outliers (c) Residual probability plot with outlier (d) Residual probability plot without outliers

Fig. 7. lognormal probability plot

Fig. 8. (a) Impact of $V_{out-opt}$ on $\Delta\tau$ (b) lognormal probability plot of different $V_{out-opt}$.

Fig. 9. (a) Lifetime vs. Stress (b) Acceleration Factor vs. Stress

Fig. 10. Aging simulation and Device stress (13V group)

Fig. 11. Aging simulation results $\Delta V_{knee}(t)$ vs. t

Fig. 13. Extrapolation comparison

Fig. 12. Correlations between degradation parameters $\beta_{1\sim 2}$ and voltage stress

TABLE I
STRESS TEST CONDITION

Stress level	Stress point	Sample size	Ambient temperature	Loading current	Test time	Hard failure
9V	Output node	8	25°C	Rated value	1104 hr	0
11V	Output node	9	25°C	Rated value	1104 hr	0
13V	Output node	9	25°C	Rated value	1104 hr	0

TABLE II
ESTIMATED DEGRADATION PARAMETERS $\theta_{\beta} = (\mu_{\beta}, \Sigma_{\beta})$

θ_{β}	μ_{β}	Σ_{β}
9V group	$\begin{pmatrix} 0.009 \\ 0.144 \\ 0.772 \end{pmatrix}$	$1e-4 \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0.713 & 0 \\ 0 & 0 & 0.354 \end{pmatrix}$
11V group	$\begin{pmatrix} 0.020 \\ 0.136 \\ 0.770 \end{pmatrix}$	$1e-4 \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0.957 & 0 \\ 0 & 0 & 0.298 \end{pmatrix}$
13V group	$\begin{pmatrix} 0.048 \\ 0.081 \\ 0.774 \end{pmatrix}$	$1e-4 \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0.199 & 0 \\ 0 & 0 & 0.269 \end{pmatrix}$