Reliability Prediction Modeling of Semiconductor Light Emitting Device

Jingsong Xie, *Member, IEEE*, and Michael Pecht, *Fellow, IEEE*

***Abstract*—This paper presents a probabilistic-approach-based reliability prediction model of semiconductor light emitting devices. Using this model with given initial light-emitting performance and degradation behavior otherwise determined by experiment, the reliability function of the devices is obtained, and the results correlate well with experimental results. (Modeling the initial light-emitting performance and the degradation behavior is still an on-going effort and is not included in this paper. Eventually, this model will include both parts of the modeling to provide complete analytical results of reliability prediction.) This study is a step to develop a complete physics-of-failure-based reliability prediction methodology for semiconductor light-emitting devices. It provides an approach and proves the feasibility of determining a reliability function based on fundamental parameters of device performance.**

***Index Terms*—Accelerated life test, confidence level, light-emitting diode (LED), log-normal distribution, reliability, semiconductor light-emitting device.**

I. Introduction

Semiconductor light-emitting devices have been widely used in displays, optical sensing, signal sources, and light sources. Nowadays, semiconductor light-emitting devices are designed into many electronic products. For example, in optical tracking engines built in optical mice, light-emitting diodes (LEDs) are used as a light source and the light power delivered onto the tracking surface is essential for the functioning of the optical tracking system.

Although technological advances in recent years have dramatically improved their performance, reliability remains an issue for LEDs [1]–[5]. For example, although LEDs have a nominal operational life of over a million hours, depending upon the application and performance requirements, it can still be difficult to locate a reliable LED component with a life span of 10 000 to 50 000 hours, which usually covers the warranty life of 3–5 years for a commercial product.[1] Compared to other optical and digital applications, a light source device tends to operate with high current to produce sufficient light output for the required function.

Traditionally, reliability engineers have used the MIL-HDBK-217 and progeny (e.g., Telcordia SR-332, RAC's PRISM, SAE's reliability prediction method, and the CNET reliability prediction model) for reliability prediction of electronic devices such as LEDs. These handbooks suffer from various shortcomings as per the IEEE 1413.1 standard. In particular, they do not consider the effect of design and manufacturing process on the reliability of the devices on a sufficiently scientific basis [6], do not provide a definition of the failures and failure criteria (failure modes and mechanisms), or do not give any confidence level of the predictions. As a result, the reliability metrics derived from the handbook methods are not indicative of real in-field reliability.[2]

Testing remains the most common approach to reliability assessment in industry. Using accelerated testing, designers can complete a life test of semiconductor light-emitting devices within a few weeks [8]–[10]. However, using accelerated testing to predict reliability of electronic devices in a quantitative manner is a challenge. First, one needs an acceleration model to predict reliability using accelerated testing. For example, one of the most widely used acceleration models is the Arrhenius model, particularly for semiconductor devices such as the light-emitting device. Second, to determine the probabilistic value of reliability including its statistics, such as mean time to failure (MTTF) and the hazard rate, one also needs a probabilistic distribution model. Unfortunately, studies and industry practice so far have indicated that neither the Arrhenius model, which considers the environmental condition of only constant temperature, nor the exponential distribution model developed on the basis of constant failure rate are suitable for the reliability prediction of semiconductor light-emitting devices [1].

Depending upon testing to determine the final form of reliability functions is a major obstacle of developing an analytical approach for reliability prediction and evaluation. To be able to predict the reliability of an electronic device before or without testing a product, a physics-of-failure-based relationship between the reliability function of the device and its design, manufacturing process, packaging material, and operating conditions needs to be established. As the first step to achieve the goal for semiconductor light-emitting devices, this study provides an approach to acquire the reliability function of semiconductor light-emitting devices by analyzing the probabilistic

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The authors are with the CALCE Electronic Products and Systems Center, University of Maryland, College Park, MD 20742 USA (e-mail: jsxie@calce.umd.edu).

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[1]For example, three years has about 26 300 hours. If a device operates eight hours a day and five days a week, five years of life is equivalent to 10 400 hours of operation.

[2]To provide a consistent way of evaluating reliability predictions, IEEE Standard 1413 was developed. An IEEE 1413-compliant reliability prediction includes sufficient information regarding the inputs, assumptions, and uncertainties associated with a prediction method to enable the users to understand the risks associated with its use. IEEE 1413.1 is a guide that provides assistance in the selection and use of reliability prediction methodologies, and thus helps in making informed decisions regarding the compliance of various methodologies to IEEE 1413.

characteristics of basic random variables, although the probabilistic characteristics of the basic random variables themselves have yet to be otherwise obtained by experiment. These characteristics include the variation of a device's initial light-emission performance, which defines the basic manufacturing quality of the device. This study is to pave the way for follow-on research of integrating device design, manufacturing, and operating conditions into the probabilistic model for a complete analytical reliability prediction of semiconductor light-emitting devices.

II. Light Emission and Degradation

Radiation output, which is measured either in radiometry or in photometry, is the essential measure of the performance of a light-emitting device. Therefore, the degradation of semiconductor light-emitting devices can be described by a deceasing radiation intensity, I_V, with operation time t. Previous studies have given the following relation to describe such degradation behavior [2]:

$$I_V = I_{V0} e^{-\alpha t} \tag{2.1}$$

where I_{V0} is the initial value of the radiation intensity I_V, and α is the degradation constant determined by device chemistry and structure, manufacturing process, packaging material, and operational conditions, such as environmental temperature, humidity, and operating current. This degradation relation is primarily obtained from experiments, and as a result, α is unknown as a function of the parameters listed above. It will be the subject of future work to determine the relationship between α and the parameters based on the failure mechanisms that contribute to the degradation.

Due to variations in semiconductor manufacturing and packaging processes, the performance of each individual device varies. Such variation in the performance of semiconductor light-emitting devices is a result of the random distributions of both the initial performance and the degradation characteristics of the device. Fig. 1 shows some typical distributions of LEDs' luminous intensity plotted on a log-normal distribution paper. The linearity of the data in the plot indicates a good correlation of log-normal distributions to the variations of LEDs' radiation output. We assume that the initial radiation intensity of semiconductor light-emitting devices complies with a log-normal distribution, i.e.,

$$f_{I_{V_o}}(I_{V0}) = \frac{1}{\sqrt{2\pi}\sigma' I_{V0}} e^{\frac{-(\ln I_{V0} - \mu')^2}{2\sigma'^2}} \tag{2.2}$$

where σ' and μ' are both parameters of the distribution and $0 < I_{V0} < +\infty$. In fact, in most cases, this distribution of the initial radiation intensity is also close to a normal distribution, because a log-normal distribution mathematically approaches a normal distribution when its peak distribution region narrows and moves far away from the original point (i.e., $\mu \rightarrow +\infty$ and $\sigma/\mu \rightarrow 0$) [10].

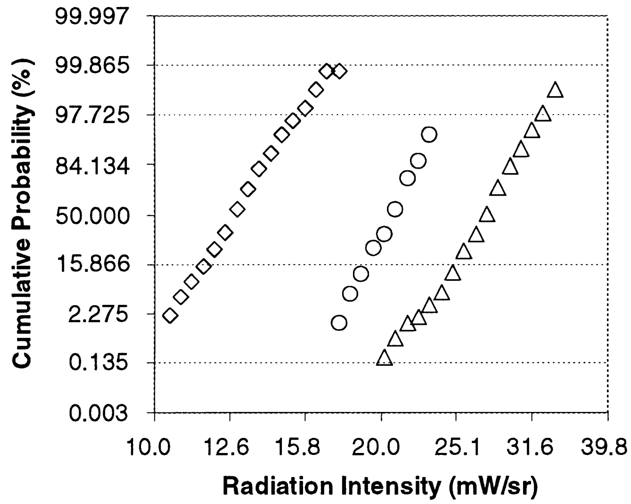

Fig. 1. Cumulative probability of LEDs' initial radiation intensity plotted in a log-normal distribution paper. The samples are 5-mm red LED lamps (600–650 nm) from three different manufacturers with the radiation intensity measured at 20 mA.

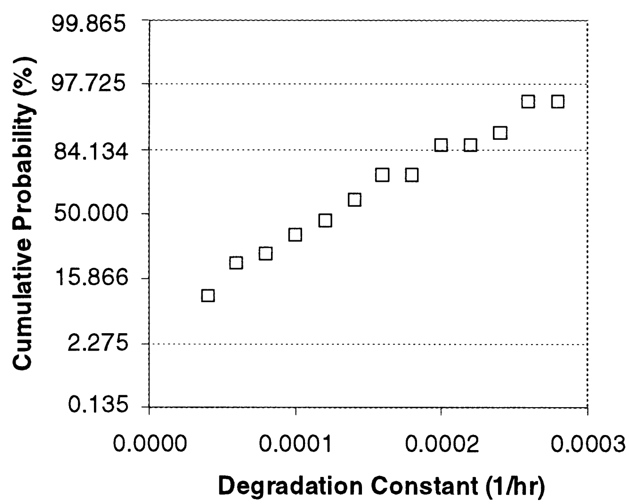

Fig. 2. Cumulative probability of LEDs' degradation constant plotted using a normal distribution paper (the data obtained from a 20 mA test of 5-mm red LED lamps).

For similar consideration, a truncated normal distribution could be assumed for the degradation constant (see Fig. 2). The distribution is therefore given by

$$f_\alpha(\alpha) = \frac{1}{A\sqrt{2\pi}\sigma} e^{-\frac{(\alpha-\mu)^2}{2\sigma^2}} \tag{2.3}$$

where σ is standard deviation and μ is the mean. Because of the positive value of the degradation constant, the distribution of (2.3) is truncated equally from both sides of the mean value, i.e., $\mu - n\sigma \leq \alpha \leq \mu + n\sigma$. In addition, a constant A is used as a corrective factor to maintain the total probability of 1 for the distribution of (2.3) and is given by

$$A \equiv \int_{\mu-n\sigma}^{\mu+n\sigma} \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(x-\mu)^2}{2\sigma^2}} dx. \tag{2.4}$$

III. Distribution of Radiation Intensity I_V

From (2.1) that the random behavior of the light radiation intensity I_V at any operation time t is determined by the distribution of the initial radiation intensity I_{V0} given by (2.2) and the distribution of the degradation constant α given by (2.3) and (2.4). Assuming that the two random variables, the initial radiation intensity and the degradation constant are independent, the cumulative probability function (CPF) of I_V is determined by the convolution of the probability density functions (PDFs) of I_{V0} and α. Considering the domain of $0 < I_{V0} < +\infty$ for I_{V0} and $\mu - n\sigma \le \alpha \le \mu + n\sigma$ for α (see Fig. 3)

$$F_{I_V}(I_V) \equiv \int_0^{I_V} f_{I_V}(I_V)dI_V = \int_{\mu-n\sigma}^{\mu+n\sigma} d\alpha \int_0^{I_V e^{\alpha t}} f_{I_{V0}}(I_{V0})f_\alpha(\alpha)dI_{V0} \quad (3.1)$$

where $F_{IV}(I_V)$ is the CDF and $f_{IV}(I_V)$ is the PDF of I_V. To obtain the expression of PDF $f_{IV}(I_V)$, the integration of (3.1) is transformed from $dI_{V0}d\alpha$ to $d\alpha dI_V$ using the Jacobian of the transformation [11]. Using (2.1), the transformation gives

$$dI_{V0}d\alpha = e^{\alpha t} d\alpha dI_V. \quad (3.2)$$

Then, plugging (2.1) and (3.2) into (3.1) and modifying the integration limits for the same integration domain (see Fig. 3) gives

$$\int_0^{I_V} f_{I_V}(I_V)dI_V = \int_0^{I_V} dI_V \int_{\mu-n\sigma}^{\mu+n\sigma} f_{I_{V0}}(I_V e^{\alpha t})f_\alpha(\alpha)e^{\alpha t}d\alpha. \quad (3.3)$$

Comparing both sides of (3.3) leads to

$$f_{I_V}(I_V) = \int_{\mu-n\sigma}^{\mu+n\sigma} f_{I_{V0}}(I_V e^{\alpha t})f_\alpha(\alpha)e^{\alpha t}d\alpha. \quad (3.4)$$

As one can see, (3.4) is a distribution function of radiation intensity I_V and an ordinary function of operation time t. Combining (2.2) and (2.3) with (3.4) results in

$$f_{I_V}(I_V) = \int_{\mu-n\sigma}^{\mu+n\sigma} \frac{1}{\sqrt{2\pi}\sigma' I_V} e^{-\frac{\left(\alpha - \frac{\mu' - \ln I_V}{t}\right)^2}{2\left(\frac{\sigma'}{t}\right)^2}} \cdot \frac{1}{A\sqrt{2\pi}\sigma} e^{-\frac{(\alpha-\mu)^2}{2\sigma^2}} d\alpha. \quad (3.5)$$

To further simplify (3.5), consider the following algebraic identity:

$$\frac{(x-\mu_1)^2}{2\sigma_1^2} + \frac{(x-\mu_2)^2}{2\sigma_2^2} \equiv \frac{\left(x - \frac{\mu_1\sigma_2^2 + \mu_2\sigma_1^2}{\sigma_1^2+\sigma_2^2}\right)^2 + \frac{(\mu_1-\mu_2)^2\sigma_1^2\sigma_2^2}{\left(\sigma_1^2+\sigma_2^2\right)^2}}{\frac{2\sigma_1^2\sigma_2^2}{\sigma_1^2+\sigma_2^2}}. \quad (3.6)$$

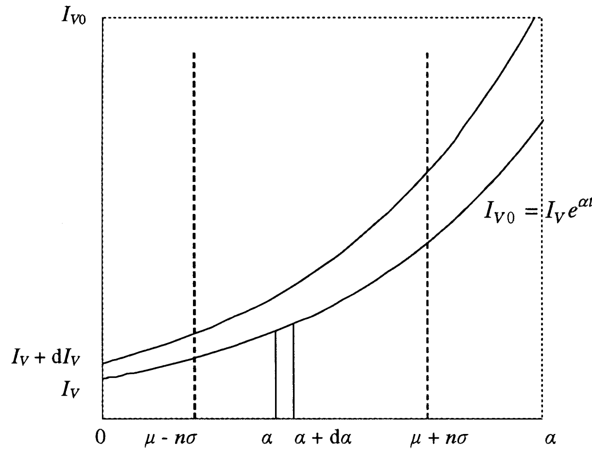

Fig. 3. Domain and integral limits of the random variables, I_{V0}, α, and I_V with the shadowed area for (0, I_V).

Also paying attention to the relations

$$\mu_1 \equiv \frac{\mu' - \ln I_V}{t}, \ \sigma_1 \equiv \frac{\sigma'}{t} \quad (3.7a)$$

$$\mu_2 \equiv \mu, \ \sigma_2 \equiv \sigma \quad (3.7b)$$

and $x \equiv \alpha$ for this case, one will have

$$f_{I_V}(I_V) = \frac{1}{A\sqrt{2\pi}\sqrt{\sigma'^2 + t^2\sigma^2} I_V} e^{-\frac{[\ln I_V - (\mu' - t\mu)]^2}{2(\sigma'^2 + t^2\sigma^2)}} \times \int_{B_1(I_V,t)}^{B_2(I_V,t)} \frac{1}{\sqrt{2\pi}} e^{-\frac{x^2}{2}} dx \quad (3.8)$$

where the upper and lower integral limits $B_1(I_V,t)$ and $B_2(I_V,t)$ are functions of t, and given by

$$B_1(I_V,t) \equiv \frac{-n\sqrt{\sigma'^2+t^2\sigma^2}}{\sigma'} + \frac{t\sigma}{\sigma'} \cdot \frac{\ln I_V - (\mu' - t\mu)}{\sqrt{\sigma'^2+t^2\sigma^2}} \quad (3.9a)$$

$$B_2(I_V,t) \equiv \frac{n\sqrt{\sigma'^2+t^2\sigma^2}}{\sigma'} + \frac{t\sigma}{\sigma'} \cdot \frac{\ln I_V - (\mu' - t\mu)}{\sqrt{\sigma'^2+t^2\sigma^2}}. \quad (3.9b)$$

In (3.8), x replaces α as the integral variable. As one can see, given the initial performance of a semiconductor light-emitting device by (2.2) and the degradation characteristics by (2.3), (3.8) provides the distribution of radiation intensity I_V at any duration t for which the device operates.

IV. Reliability Function

To determine reliability, the failure criterion of minimum radiation intensity I_{Vmin} is first defined, considering the basic performance requirement on light-emitting device, i.e., a device is considered as failed when its radiation goes below some minimum value I_{Vmin}. Using the failure criterion, the CPF of I_V

is determined by integrating (3.8) from 0 to I_{Vmin}. To do that, a new integral variable of y is defined as

$$y \equiv \frac{\ln I_V - (\mu' - t\mu)}{\sqrt{\sigma'^2 + t^2\sigma^2}}. \tag{4.1}$$

Substituting (4.1) into (3.8), (3.9), and reorganizing the equations gives a two-dimensional integral

$$\begin{aligned} F_{I_V}(I_{V\min}) &\equiv \int_0^{I_{V\min}} f_{I_V}(I_V)dI_V \\ &= \int_{-\infty}^{\frac{\ln I_{V\min}-(\mu'-t\mu)}{\sqrt{\sigma'^2+t^2\sigma^2}}} dy \frac{1}{A\sqrt{2\pi}} e^{-\frac{y^2}{2}} \\ &\quad \times \int_{C_1(y,t)}^{C_2(y,t)} \frac{1}{\sqrt{2\pi}} e^{-\frac{x^2}{2}} dx \end{aligned} \tag{4.2}$$

where

$$C_1(y,t) \equiv \frac{-n\sqrt{\sigma'^2 + t^2\sigma^2}}{\sigma'} + \frac{t\sigma}{\sigma'}y \tag{4.3a}$$

$$C_2(y,t) \equiv \frac{n\sqrt{\sigma'^2 + t^2\sigma^2}}{\sigma'} + \frac{t\sigma}{\sigma'}y. \tag{4.3b}$$

Equation (4.2) is the probability of failure; that is, the percentage failure of a group of samples after being operated for a period time t. In other words, the probability given by (4.2) is also the probability of a sample whose operational life[3] (or time-to-failure) is shorter than t. Considering the time t as a random variable of time-to-failure this time, one obtains the time-to-failure function

$$F(t) = \int_{-\infty}^{\frac{\ln I_{V\min}-(\mu'-t\mu)}{\sqrt{\sigma'^2+t^2\sigma^2}}} dy \frac{1}{A\sqrt{2\pi}} e^{\frac{-y^2}{2}} \int_{C_1(y,t)}^{C_2(y,t)} \frac{1}{\sqrt{2\pi}} e^{-\frac{x^2}{2}} dx. \tag{4.4}$$

The reliability function $R(t)$ is then given by $1 - F(t)$. The time-to-failure density function is obtained by taking the derivative of (4.4)

$$f(t) = \frac{dF(t)}{dt}. \tag{4.5}$$

To do that, one substitutes (4.4) in (4.5) while paying attention to the following derivative identity:

$$\frac{d}{dt}\int_a^{g(t)} h(t,y)dy = h\left(t, g(t)\right) g'(t) + \int_a^{g(t)} h'_t(t,y)dy \tag{4.6}$$

where a is a constant, and obtain the PDF of time-to-failure t, which can be expressed in terms of

$$\begin{aligned} f(t) &= \frac{1}{A\sqrt{2\pi}} g'(t) \cdot e^{-\frac{g^2(t)}{2}} \int_{C_1[g(t),t]}^{C_2[g(t),t]} \frac{1}{\sqrt{2\pi}} e^{-\frac{x^2}{2}} dx \\ &\quad + \int_{-\infty}^{g(t)} dy \frac{1}{A\sqrt{2\pi}} e^{-\frac{y^2}{2}} \cdot \frac{1}{\sqrt{2\pi}} \\ &\quad \times \left[\frac{\partial C_2(y,t)}{\partial t} e^{-\frac{C_2^2(y,t)}{2}} - \frac{\partial C_1(y,t)}{\partial t} e^{-\frac{C_1^2(y,t)}{2}}\right] \end{aligned} \tag{4.7}$$

where $g(t)$ is given by

$$g(t) \equiv y|_{I_V = I_{V\min}} = \frac{\ln I_{V\min} - (\mu' - t\mu)}{\sqrt{\sigma'^2 + t^2\sigma^2}}. \tag{4.8}$$

Now, from the initial performance of a semiconductor light-emitting device given by (2.2) and the degradation characteristics given by (2.3), the time-to-failure function of the device of (4.4) for cumulative probability and (4.7) for probability density has been determined.

V. Comparison With Experimental Results

This study provides an approach to determine the reliability function [i.e., $1 - F(t)$, $F(t)$ given by (4.4)] from given degradation behavior and its random characteristics [i.e., (2.1)–(2.4)], otherwise determined by experiment. The purpose of this comparison is to verify the mathematical process as well as the degradation assumptions used in the modeling.

In the experiment, a life test of 130 AlInGaP 5-mm LED lamps was performed at an operating current of 100 mA, which is higher than the LEDs' rated operating current of 20 mA, to reduce the test time. First, the initial radiation output and degradation constant, used in the model for time-to-failure prediction, were obtained from the experimental data and the results are provided in Table I. The results show that the samples have an average initial light output of about 100 mW/Sr at 100 mA and degrade 50% in an average time period of about 70 h. Using the experimental data in Table I, at any given time-to-failure t, the two-dimensional integral of (4.4) can be calculated to obtain the analytical results[4] on cumulative probability of failure. Then, all of the samples were tested to failure so that time-to-failure probability became experimentally available by determining the samples' percentage failure for different lengths of operation time. A comparison was then made between the two results on time-to-failure probability for the operating current condition of 100 mA.

Fig. 4 shows the comparison of the experimental and analytical results on probability of failure plotted in a log-normal paper. It can be seen that the analytical results correlate well with the experimental results. In addition, both results show good linearity in the plot, again indicating that the time-to-failure function and the reliability function of LEDs can be approximately modeled with a log-normal distribution. The results shown in Fig. 4 also make it clear that the distribution is not exponential as assumed by the MIL-HDBK-217 and Telecordia prediction methods. In addition, it should not be mistakenly considered that the exponential distribution shown in Fig. 4 is linear in a log-normal paper, because it is only a fraction of the entire curve.

[3]Since item repair is not a topic discussed in this article, the term "operational life" and "time-to-failure" are considered the same and used identically.

[4]More accurately speaking, the results obtained from the model are semi-analytical due to the involvement of experimental data in the analysis. Note that all "analytical" results referred in the following text have this nature.

TABLE I
INITIAL RADIATION PERFORMANCE, DEGRADATION CHARACTERISTICS, AND FAILURE CRITERION USED IN THE RELIABILITY PREDICTION

Parameter	Value	Unit
μ' and σ' in (2.2)	4.632 and 0.825	Natural logarithm of mW/Sr
μ and σ in (2.3)	0.096 and 0.052	1/hr
n and A in (2.4)	1.85 and 0.9357	N/A
Failure criterion in percentage degradation $I_{Vmin}/e^{\mu'}$	10	%

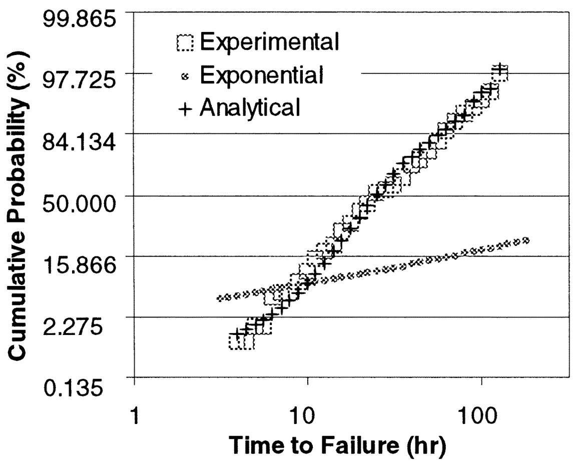

Fig. 4. Comparison between experimental results and the analytical results obtained from (4.4) on reliability prediction of an LED operated at 100 mA. The experimental data analyzed using the exponential distribution is also plotted to show its difference from the other two.

VI. CONCLUSIONS AND FUTURE WORK

A reliability prediction model is developed for semiconductor light-emitting devices. The comparison between the analytical and experimental results on LEDs verifies the effectiveness of the model to predict time-to-failure probability or reliability of semiconductor light-emitting devices given their initial light-emitting performance and degradation characteristics. In addition, this comparison reveals that the time-to-failure function and reliability function of LEDs can be represented by a log-normal distribution.

As future work, this model still needs an analytical approach to determine the initial radiation performance and the degradation characteristics of a semiconductor light-emitting device so that a complete analytical prediction becomes possible. In addition, its device structure and chemistry, manufacturing process, packaging material, and operational conditions should be included to predict the reliability of the device based on its manufacturing quality and operational conditions.

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Jingsong Xie (S'98–A'00–M'03) received the B.S. degree in engineering mechanics from Tsinghua University, China, the M.S. degree in naval architecture and ocean engineering from Tokyo University, Japan, and the Ph.D. degree in mechanical engineering from the University of Maryland, College Park.

He is currently a Research Faculty Member with the CALCE Electronic Products and Systems Center at the University of Maryland. He was previously a Component Reliability Engineer with Microsoft and a Visiting Assistant Professor in the University of Maryland. His research interests include electronic component reliability and qualification and other areas including thermal management and EMI/EMC. He is an author of over 20 technical publications.

Dr. Xie is a member of the American Society of Mechanical Engineers (ASME) and the International Microelectronics and Packaging Society (IMAPS).

Michael Pecht (S'82–M'83–SM'90–F'92) received the B.S. degree in acoustics, the M.S. degree in electrical engineering, and the M.S. and Ph.D. degrees in engineering mechanics from the University of Wisconsin, Milwaukee.

He is the Director of the CALCE Electronic Products and Systems Center at the University of Maryland, College Park, and a Full Professor with a three-way joint appointment in Mechanical Engineering, Engineering Research, and Systems Research. He serves on the boards of advisors for various companies and consults for the U.S. government, providing expertise in strategic planning in the area of electronics products development and marketing.

Dr. Pecht is a Professional Engineer and a Fellow of the American Society of Mechanical Engineers (ASME). He served as Chief Editor of the IEEE TRANSACTIONS ON RELIABILITY for eight years and on the advisory board of IEEE *Spectrum*. He is currently the Chief Editor for *Microelectronics Reliability*, an associate editor for the IEEE TRANSACTIONS ON COMPONENTS, PACKAGING, AND MANUFACTURING TECHNOLOGY, and on the advisory board of the *Journal of Electronics Manufacturing*.