Measurement and Prediction of Efficiency Loss in LEDs

Kiel Strang, Laura Greenstreet
Science One Program
The University of British Columbia
Vancouver, Canada
April 2012

Abstract.
An order of magnitude improvement in power efficiency of light emitting diodes (LEDs) over incandescents makes them ideally suited for a variety of applications. GaInN LEDs, used to produce white light, exhibit a loss of efficiency with increased power. By measuring the efficiency of GaInN and GaAs LEDs we found losses beginning within their rated range. Linear regression allowed us to develop polynomial and power law models for efficiency loss. Models were evaluated using measurements at high power, with the power law model providing the best fit. Our results suggest further research should be conducted on temperature-related efficiency loss and its underlying causes.

1 Introduction

The development of gallium nitride LEDs during the mid-1980s was heralded as a breakthrough in energy efficient lighting, creating the possibility of developing installations with 2.5 times the efficiency of fluorescent lighting without the use of toxic mercury (Stevenson 2009). However, high costs and a decrease in light generation efficiency at high power, known as droop, have limited implementation of the devices. Current applications of LEDs include backlights for electronic devices, signs and displays, and cellphone camera flashes (Global Industry Analysts Inc. 2010). Applications under development include television displays and lighting installations (Global Industry Analysts Inc. 2010). However, the issue of droop must be addressed before the devices can become ubiquitous.

The classic incandescent lightbulb creates light by heating a tungsten filament until photons are released, resulting in efficiencies of only 16 lumens/Watt with 90% of power being dissipated as heat (Stevenson 2011). In fluorescent lightbulbs a current excites the atoms in a gas, resulting in an improved light output of 100 lumens/Watt (Stevenson 2011). LEDs allow for a significant improvement over these efficiencies generating 250 lumens/Watt (Stevenson 2009). The mechanism of LED light generation is key to its higher efficiency.

LEDs consist of two semiconductor layers doped with electron-rich and electron-deficient atoms separated by a thin semiconductor layer, known as the active region (Stevenson 2009). The electron rich layer is denoted 'n-type' material while the electron deficient region is denoted 'p-type'. The missing electrons in the p-type material are referred to as holes. When a voltage is applied across the device, holes and electrons migrate to the active region and recombine, releasing a photon. The wavelength of light produced is determined by the ratio of dopants in the semiconductor (Stevenson 2009).

To manufacture LEDs, doped semiconductors must be grown on a substrate (Stevenson 2009). The closer the spacing of the atomic structure of the substrate to the LED the fewer defects in the resultant semiconductor, resulting in the production of more efficient LEDs from substrates with similar structures. Long wavelength GaAs LEDs can be manufactured on structurally-identical gallium arsenide, resulting in low-defect devices. However there is a deficit of substrates suitable for growing low wavelength GaInN LEDs. Currently gallium nitride LEDs are manufactured on sapphire wafers, leading to devices full of defects (Stevenson 2009).

As the power through a gallium nitride LED increases, the ratio of light output to power input plummets (Stevenson 2009). While the phenomenon has been known since the 1990s, scientists have yet to develop a satisfactory explanation for droop. Three explanations are currently under consideration: recombination of the electrons with the p-type material giving limited photon emission; prevention of recombination by internal electric fields; and recombination of holes and electrons without photon emission (Auger recombination) (Stevenson 2009). Chris Van de Walle of UC Santa Barbara and Weng Chow of Sandia National Laboratories have developed models placing varying weights on each explanation (Chow 2011, Van de Walle *et al.* 2011). However, their simulations have been unable to accurately match experimental observations (Stevenson 2011).

Through the measurement of light output of commercial LEDs, we planned to determine if droop is observable in consumer products. We measured emission efficiency at a variety of power levels, using a lux meter to measure light output from LEDs connected to a variable voltage power supply. Previous research by Qi Dai *et al.* (2007) indicates that droop is observable below the LEDs 20 mA current rating. Through the measurement of LEDs with a variety of wavelengths and consistent dimensions, we aimed to establish that droop is dependent on semiconductor structure and independent of wavelength. Based on low power data, we developed a mathematical model for LED droop and tested the accuracy of our model with measurements at high power.

2 Methods

Through our tests we wished to investigate whether droop is dependent on nitride content and independent of wavelength. We tested three replicates of eight models of LED manufactured from MODE Electronics Ltd. to evaluate a range of wavelengths and substrate materials (See Table 1). All LEDs were 5 mm domed models to make light emission conditions, such as junction size and shape, as uniform as possible.

Model	**Color**	**Wavelength (nm)**	**Material**	**Type**	**Variance** (%)
55-552-5	Red	700	GaP	Regular	–
55-557-2	Red	660	GaAlAs	Ultrabright	3.63
55-554-2	Yellow	586	AlGaInP	Ultrabright	7.14
55-555-5	Green	568	GaP	Regular	–
55-555-1	Green	525	InGaN	Ultrabright	1.24
55-558-2	Blue	470	InGaN	Ultrabright	1.94
55-558-1	Blue	468	InGaN	Ultrabright	1.87
110-506	Blue	465	InGaN	Ultrabright	1.08

Table 1: Specifications for LEDs used in the experiment. Wavelength and substrate type were provided by MODE Electronics (MODE Electronics Ltd.). Variance was measured by recording the light output at 10 mA for the same LED replicate five times, reassembling the setup between each measurement. The percentage was obtained by calculating the standard deviation as a percentage of the mean of the five measurements.

Control over current levels to $\pm$ 0.5 mA was obtained by creating a circuit consisting of a 220 Ω resistor in series with an LED connected to a 15 V JDR Microdevices PDS-500 variable voltage power supply (See Figure 1). Equus 4320 and Beckmann Industrial DM27Xl multimeters were used to measure current and voltage values for the circuit as voltage was varied. Each replicate was tested throughout its rated 20 mA range at 0, 4, 6, 8, 10, 12, 14, 16, 18, and 19 mA current levels. 10 mA readings were taken at both beginning and end of each replicate to ensure the apparatus was taking consistent measurements. Power values were calculated by taking the product of the current and the voltage. A black plastic shell was placed behind each LED to prevent light from being reflected off the power supply and onto the light sensor.

A lux is defined as a lumen per meter squared and measures the amount of light from regions of the electromagnetic spectrum perceived humans (Merriam-Webster 2003). In constrast, power measures the total amount of energy from all regions of the spectrum per square meter. Lux levels were measured using a Gigahertz Optik HCT-99 Color Meter, which measures lux via four photodiodes sensitized to regions of the visible spectrum percieved by cones in the human eye (Gigahertz Optik 2012). Since lux is dependent on distance from the device, the meter was held in a constant position using a vice. At the start and end of each measurement session, ambient lux levels were measured and found to be stable and not to exceed 3.00 lux. While the ambient lux was found to be less than 2% of the lux measured for each ultrabright LED it was found to be up to 100% of the lux output of the regular LEDs. As a result, we did not analyze the regular LEDs in our models. LEDs were aligned with their beam centered on the light meter

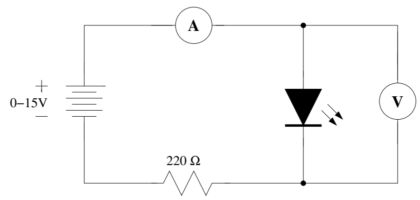


Fig. 1: Schematic of the test circuit.

sensor. However, movements of even a few millimetres were found to cause changes in the magnitude of lux as large as 50%. Once an LED was aligned with the sensor it remained stationary for the rest of the measurements. Additionally, five measurements of a single LED of each type at 10 mA were taken to quantify random error in the experimental setup.

Once we had developed models for the droop in each LED, we measured an additional three replicates at high power. Measurements were taken at 10 mA for the purpose of matching previous measurements, in addition to 35, 40, 45, and 50 mA levels. During these tests a switch was used to limit the time each LED was exposed to high power, to minimize heating of the junction. 10 mA measurements taken at the end of each test indicated no damage to the LEDs.

3 Results

To provide a large enough data set to create a model, the data from the three replicates of each LED were combined. To account for variation in the magnitude of lux due to sensor alignment, data were analyzed in terms of the ratio of light output to power input with respect to the 10 mA ratio. Since no measurements were taken at exactly 10 mA, our Matlab scripts normalizaed the data using the measurement closest to 10 mA. This choice of scaling allowed the magnitude of droop to be observed regardless of the lux meter's sensitivity to wavelength or exact alignment of each LED with the sensor. For each type of LED, linear regression was used to create power-law and polynomial models of droop (See Table 2). A cubic regression (four parameters) was originally used for the polynomial model. However, we felt that using four parameters to fit measurements taken at 10 current values over-interpreted our data. Thus, we calculated quadratic (three parameter) regressions. Power law and quadratic fits are shown in Figure 2, with plots of individual LEDs shown in Appendix A. Since the majority of uncertainty was due to alignment of the light meter, the measured uncertainty at 10 mA is a good estimation of the uncertainty at all power levels (See Table 1).

LED	Quadratic Model	Power-Law Model
Red (55-552-5)	$y = -0.078x^2 + 1.154x - 0.087$	$y = x^{1.077}$
Yellow (55-554-2)	$y = -0.079x^2 + 1.101x - 0.046$	$y = x^{1.014}$
Green (55-555-1)	$y = -0.196x^2 + 1.141x + 0.047$	$y = x^{0.725}$
Blue (55-558-1)	$y = -0.187x^2 + 1.133x + 0.041$	$y = x^{0.737}$
Blue (55-558-2)	$y = -0.156x^2 + 1.156x - 0.005$	$y = x^{0.847}$
Blue (110-506)	$y = -0.189x^2 + 1.136x + 0.053$	$y = x^{0.719}$

Table 1: Quadratic and Power-Law Models Based on Low Power Measurements

To test the accuracy of each model's predications, we compared the models to the measurements taken between 35 and 50 mA. We normalized the high-power data against the 10 mA baseline and plotted the new data combined with the low-power measurements (See Appendix B). Incorporating the additional data, the power-law model was clearly more accurate than the quadratic model.

Based on our linear regressions, we wished to calculate a parameter that would allow comparison of droop between LEDs, determine how closely each model matched the additional high power data, and quantify which model provided more accurate predictions. Initially we applied an R^2 test, which assigned each LED a value between 0 and 1 based on the ratio of the difference between the model and the data and the difference between the data and the mean (See Equation 1). This parameter assigns higher values to models that matched the data more closely and would allow us to compare the power-law and quadratic models for both data sets. For all LEDs, the R^2 values was 0.993 ± 0.001, thus we were unable to rank the models based on the R^2 values.

$$R^2 = 1 - \frac{\sum(y_i - f_i)^2}{\sum(y_i - y)^2}. \quad (1)$$

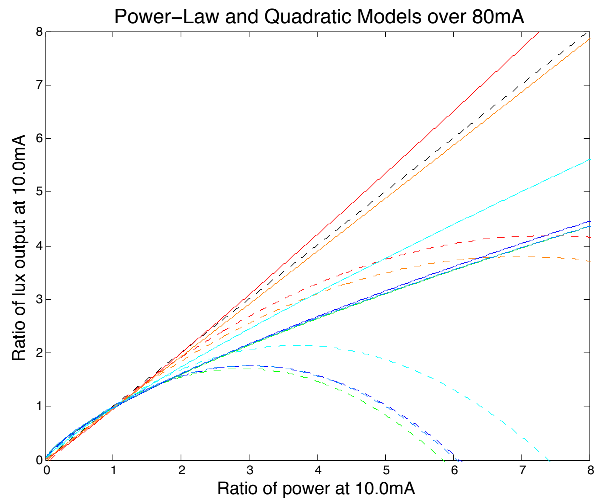


Fig. 2: Comparison of power-law and quadratic models over an 80mA range. Both models show similar behaviour at low power. However, at high power the quadratic models shows negative-increasing rates of change of light output, while the power-law models shows positive-decreasing rates of change.

A least squares test calculates the weighted average of the difference between the model and the data, calculating lower values for models which are a closer fit to the data (See Equation 2). Unlike the R^2 test, the least squares test does not weight the difference of the model from the data against the difference of the data from the mean, thus penalizing models fitting more variable data sets. However, by only calculating the difference between the model and the data, we were able to calculate values which were sufficiently distinct to compare the models.

$$\text{Least Squares} = \frac{1}{n-1}\sqrt{\sum(y_i - f_i)^2}. \tag{2}$$

To determine the accuracy of each model and the level of droop in each LED type, we calculated the least squares value for the power-law and quadratic models separately on the low-power and full data sets compared to a linear function (See Table 3). For both the red and yellow LEDs, the least squares value for the full data set was lower for the linear function than either the quadratic or power-law models, strongly evidencing they were not experiencing droop. For the GaInN LEDs, the linear fit was more than an order of magnitude worse than either the quadratic or power-law models, providing evidence that they were experiencing droop. The highest linear least squares values were found for Blue 55-558-1, indicating that it experienced the largest amount of droop. However, the similar linear least square values for all GaInN LEDs show they all experienced similar levels of droop.

LED	Linear - Low	Quad - Low	Power - Low	Linear - High	Quad - High	Power - High
Red (55-552-5)	0.067	0.036	0.067	0.279	0.409	0.426
Yellow (55-554-2)	0.071	0.026	0.041	0.108	0.347	0.077
Green (55-555-1)	0.227	0.039	0.045	0.702	0.708	0.064
Blue (55-558-1)	0.220	0.032	0.037	0.807	0.888	0.058
Blue (55-558-2)	0.170	0.027	0.044	0.680	0.740	0.014
Blue (110-506)	0.219	0.018	0.020	0.766	0.744	0.055

Table 2: Least Squares Values for Linear, Quadratic, and Power Models at Low and High Power

Using only the low power data, the least squares values for the quadratic model were slightly lower than those for the power-law model. However when the full data range was analyzed, the power-law model had least squares values an order of magnitude less than the quadratic model, showing the power model provides an order of magnitude better approximation that the quadratic model. In fact, for Blue 55-558-2, incorporating the high power data resulted in a lower least squares value for the power-law model than using the low power data alone.

To determine if wavelength was correlated with droop, we performed a linear regression of LED wavelength to the power-law coefficient and calculated the corresponding R^2 value (See Figure 3). The R^2 value was found to be 0.764, indicating any linear relationship between wavelength and droop is weak. However since we only tested LEDs at six wavelengths, our data set is too small to conclude that droop is wavelength independent with high certainty.

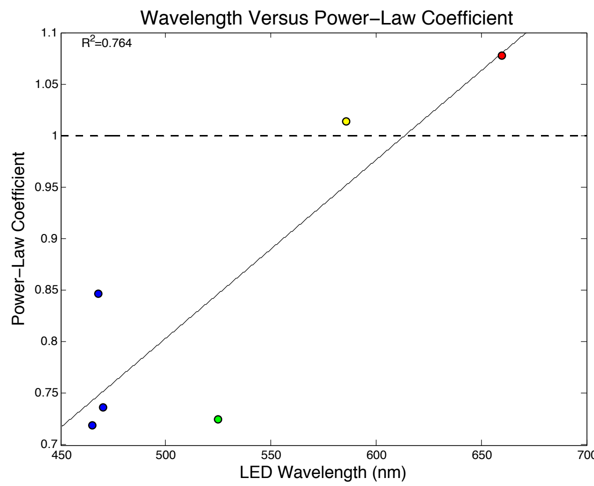


Fig. 3: Comparison of power-law model coefficient and emission wavelength. The solid line shows the linear regression for the six LEDs. The dashed line indicates the expected regression if droop was not present.

4 Discussion

Our least squares fit showed a clear departure from linear behaviour in the GaInN LEDs, providing evidence that droop is observable in consumer products. The lux to power efficiency begins to diverge from a linear fit by the 10 mA current level, half the rated current value for the devices. Thus, droop would be experienced by LEDs used under everyday conditions.

Based on both the least squares fit at low power and the exponents from the power-law model, we found that the GaAlAs controls did not exhibit significant droop, fitting most closely to a linear function. Measurements at high power showed the red control LED's efficiency began to fall once current levels rose to twice the rating for the LED. This could be due to an increase in temperature associated with the increase in power, as higher temperatures have been found to decrease efficiency (Stevenson, 2009). The linear behaviour of both control LEDs supports the claim that GaAs LEDs do not exhibit droop (Stevenson, 2009). Using the same parameters for evaluation as the controls, we found significant evidence for droop in all four GaInN LEDs. Based on the least squares values, the strongest droop was experienced by Blue 55-558-1, with the other GaInN LEDs experiencing similar efficiency reductions.

In GaInN LEDs, higher In concentrations are required to select longer wavelengths (Stevenson 2009). Thus it would be expected that the magnitude of the droop would increase as wavelength and dopant levels increased among GaInN LEDs. Since GaAs LEDs do not display droop, we predicted there would not be a linear relationship between wavelength and droop. The R^2 value of 0.764 from our wavelength versus droop plot indicates that any linear relationship between these variables is weak. Furthermore, the scatter of the three blue LEDs provides strong evidence that these two parameters are not correlated. However, our fits are based on only six wavelength values, which does not provide sufficient evidence to conclude that wavelength and droop are independent. The scatter in the blue LEDs could be explained by differences in manufacturing techniques, resulting in fewer irregularities in some substrates. This suggests some manufacturing processes might result in more efficient LEDs.

4.1 Quadratic Model

By changing the voltage delivered to the circuit we altered the current passing through the LED, changing the number of electrons passing through the device. Higher currents result in more electron-hole recombinations, resulting in the emission of more photons. If the cause of droop is related to electron density, it would be expected that droop would have a polynomial relation to power. For example if droop were caused by recombination without emission, doubling the number of electrons would proportionally double the number of holes present, creating a quadratic increase in recombination. Previous research has found evidence of polynomial relationships, with Mike Krames of Phillips Lumileds reporting that Auger recombination is cubically related to the density of carriers (Stevenson, 2009).

Our initial polynomial models used a least squares regression with four parameters. However, the small size and range of our low current data-set resulted in unreasonably close fits, with strange behaviour at higher power levels. Reducing the number of parameters to three, we generated the quadratic models shown in Table 2. Our quadratic models predict coefficients close to one for the linear term with a small negative quadratic term, showing efficiency reductions with increasing power. Using the least squares fit at low power values, the quadratic model was found to be a closer fit to the data than the power-law models (See Table 3).

As would be expected, close to zero both the light output to power input ratio and the rate of change of the ratio approach zero. However as power levels increase the negative quadratic term increases, eventually resulting in an impossibly negative light output to power input ratio. Thus, the model must become less accurate as power is increased. For all four GaInN LEDs, the high power measurements show that the polynomial fit overestimates the magnitude of the droop (See Appendix B). As shown in Table 3, the least squares fits using the full data set found the power-law fits to be an order of magnitude better than the quadratic models.

4.2 Power-Law Model

The sub-linear trend in the low power data indicates the light output to power input relationship could be described by a power-law model where the power value is taken to an exponent less than one. Using a log-log linear regression, we found that the yellow and red controls had exponents close to one, indicating they were not experiencing droop. The exponents on the GaInN LEDs ranged between 0.719 and 0.847, with lower exponents indicating higher levels of droop (See Table 2). The models predict that light emission will constantly increase as power increases, though the rate of change will decrease as power increases. This accurately describes the behaviour we observed. However, since the derivative of the function includes a negative power, the model predicts that the rate of change of the lux to power ratio is becomes infinite as power approaches zero. This violates conservation of energy, indicating that the model cannot be used to accurately predict behaviour at very low power levels.

Including the data from high power, we found that the power-law model was a very close fit for the observed behaviour. Inclusion of the high power data resulted in little change to the least squares values for all four GaInN LEDs (See Table 3). The small amount of deviation in the high power data was consistently skewed below the value predicted by the model. This could be due to a reduction in efficiency associated with increased junction temperature, which would not have been accounted for, since the model was created using low power measurements.

The choice of a power-law model was made based on experimental observations and is difficult to explain in terms of the proposed mechanisms for droop. There is no clear physical explanation for why Auger recombination, p-type recombination, or internal electric fields would result in an power-law relationship with the exponents determined.

4.3 Limitations of our Measurements and Analysis and Sources of Error

The dominant source of uncertainty was the light meter measurements. Changes in LED alignment as small as a few millimetres were found to change light measurements by more than 50%. We attempted to minimize this error by holding the light sensor in place with a vice and maintaining a constant distance between the sensor and the LED during the experiment. When aligning the LEDs, we attempted to match 10 mA light measurements among replicates so that values would be as comparable as possible. Once an LED was in place all measurements were taken without changing the device's location, ensuring a consistent relationship between values for each replicate. Additionally, we found the magnitude of lux recorded by the light meter varied greatly depending on the wavelength of the LED.

Since the absolute values for the light output measurements were so variable, we analyzed our data with respect to the ratio of the values to the measurement closest to 10 mA. This resulted in comparable data between all replicates and all LEDs. This method of analysis rests on the assumptions that efficiency differences are not dependent on the direction at which the light is emitted and that the wavelength of the LED does not change with power.

The error contributed by our electronic set up is likely negligible with respect to the error introduced by the light meter. Electronic multimeters were used to obtain readings of current and voltage to hundredth of a volt or milliamp. By repeatedly assembling the experimental set up five times for a single replicate of each LED at 10 mA, we were able to quantify the random error in our measurements by calculating the standard deviation of these measurements and dividing my the mean of the values (See Table 1). For all GaInN LEDs the random error was found to be less than 2% of the light to power ratio, while the controls had uncertainties of less than 10%.

4.4 Areas for Further Research

The results of our experiment suggest several further areas of exploration. The variability we experienced with the light meter suggests that better measurements could be achieved by using an integrating sphere to account for the light emitted in all directions and neutral density filters to eliminate the variable of light wavelength. The reduction in efficiency observed in the control combined with the power-law model's consistent underestimates of droop at high power suggest that junction temperature could contribute to droop. Further experiments allowing us to account for this variable in our models would allow for better droop estimations at high power.

The small number of wavelengths tested prevented us from determining if droop and wavelength were correlated. This relationship could be tested by measuring efficiency losses in GaAs and GaInN green LEDs of the same wavelength. Disparate droop levels would provide strong evidence for independence of these variables.

The high quality fit of the power-law model raises questions about the underlying cause of droop. None of the current explanations of the phenomenon appear to match with an such a relationship. Further research could be conducted to examine the underlying causes of LED droop.

5 Conclusion

Our results indicate that the efficiency of GaInN LEDs decreases as power increases, with losses observable within their rated power range. The control GaAs LEDs were found to display small reductions in efficiency due to increased power, likely due to increasing junction temperature. The general behaviour of the controls supports the hypothesis that substrate related droop occurs only in GaInN LEDs. Due to our limited data set, we were unable to show that droop is wavelength independent. Linear regressions indicated a power-law relationship between light output and power input. Currently proposed mechanisms for droop would not display a power-law relationship, raising questions about the underlying mechanisms of droop and suggests further research.

6 Acknowledgements

We are grateful to Dr. Michele Mossman and her student Jason Radel from the UBC Structured Surface Physics Laboratory for allowing us to perform our tests in their lab and borrow their light meter. Without their help our experiment would not have been possible. Additionally, we would like to thank the UBC Integrated Systems Lab for allowing us to borrow a variable power supply and multimeter. We would like to thank Dr. Douglas Scott for his guidance throughout the project and suggestions for data analysis. Finally, we appreciate the feedback from our peers Jenny Wang and Haley Patrick on early drafts of the report.

7 Literature Cited

Chow, W. 2011. ”Influences of Excitation-Dependent Bandstructure Changes on InGaN Light-Emitting Diode Efficiency.” arXiv:1107.0620v1 [physics.optics]. Web. 8 Mar. 2012.

Dai, Qi et al. 2007. ”Origin of Efficiency Droop in GaN-based Light-Emitting Diodes.” *Applied Physics Letters*, **91**(18): 183507.

Gigahertz-Optik. 2012. ”HCT-99D Meter CT-4501-4 Illuminance and Luminous Color Detector SRT Front Lens for Luminance and Luminous Color.” Web. 8 Mar. 2012.

Global Industry Analysts Inc. 2010. ”Light Emitting Diode (LED) - A Global Market Report.” Web. 8 Mar. 2012.

Merriam-Webster. 2003. ”Lux”. Web. 8 Mar. 2012.

MODE Electronics Ltd. ”LED Specifications.” Web. 8 Mar. 2012.

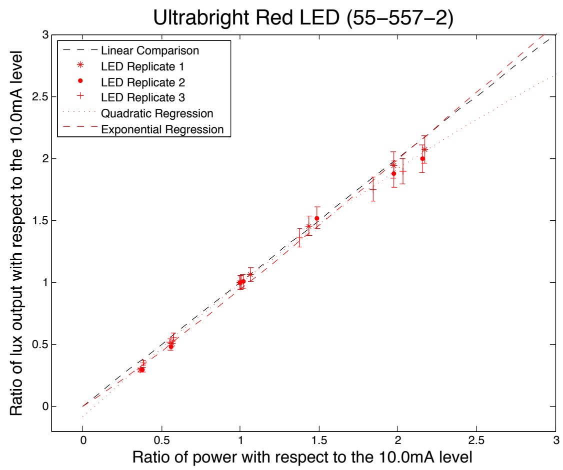
Stevenson, Richard. 2009. ”The LEDs Dark Secret”. *IEEE Spectrum*, **46**(8): 27-31.

Stevenson, Richard. 2011. ”Explaining LEDs Diminishing Returns”. *IEEE Spectrum*, **48**(11): 20.

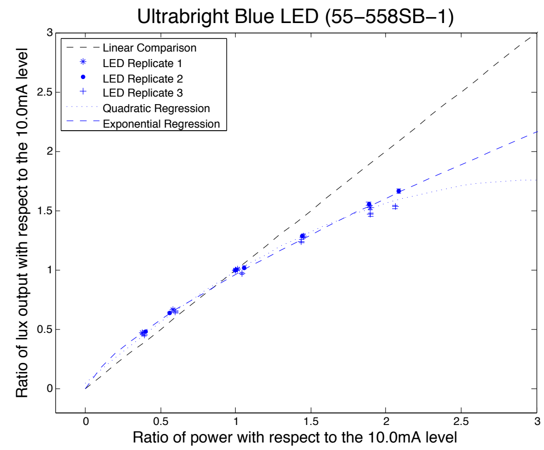
Van de Walle, C. *et al.* 2011. ”Indirect Auger Recombination as a Cause of Efficiency Droop in Nitride Light-Emitting Diodes.” *Applied Physics Letters*, **98**(16): 161107.

Appendix A – Power-Law and Quadratic Models Based on Low Power Data

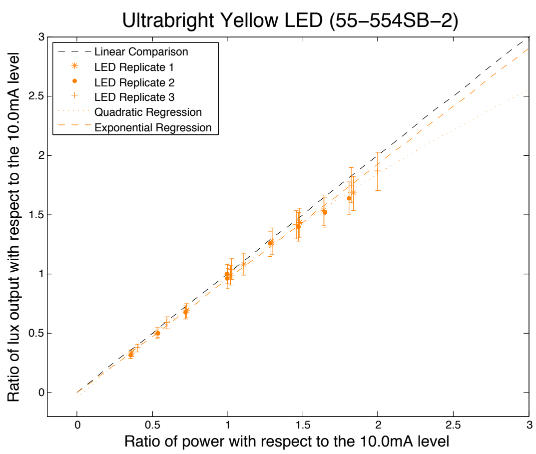
(a)



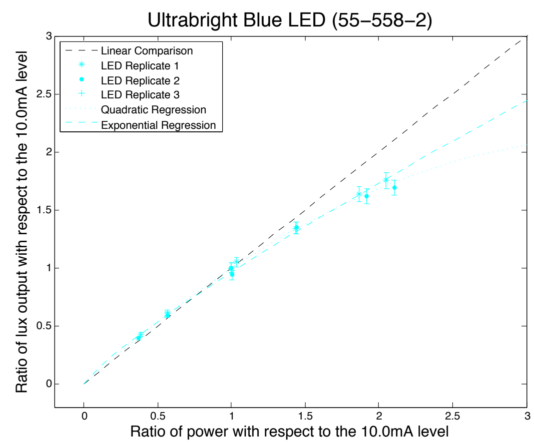
(d)



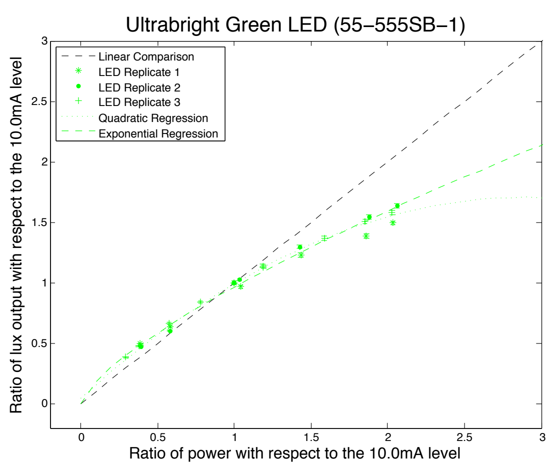
(b)



(e)



(c)



(f)

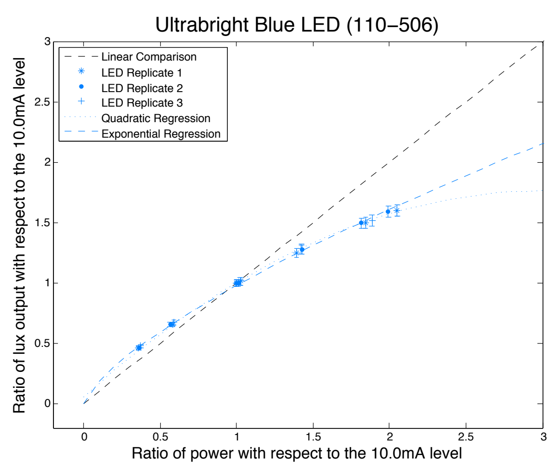


Fig. 4: Quadratic and power-law models of efficiency for the six ultrabright LEDs, shown as a ratio of light output to power input based on 10 mA baseline measurements.

Appendix B – Power-Law and Quadratic Models Incorporating High Power Data

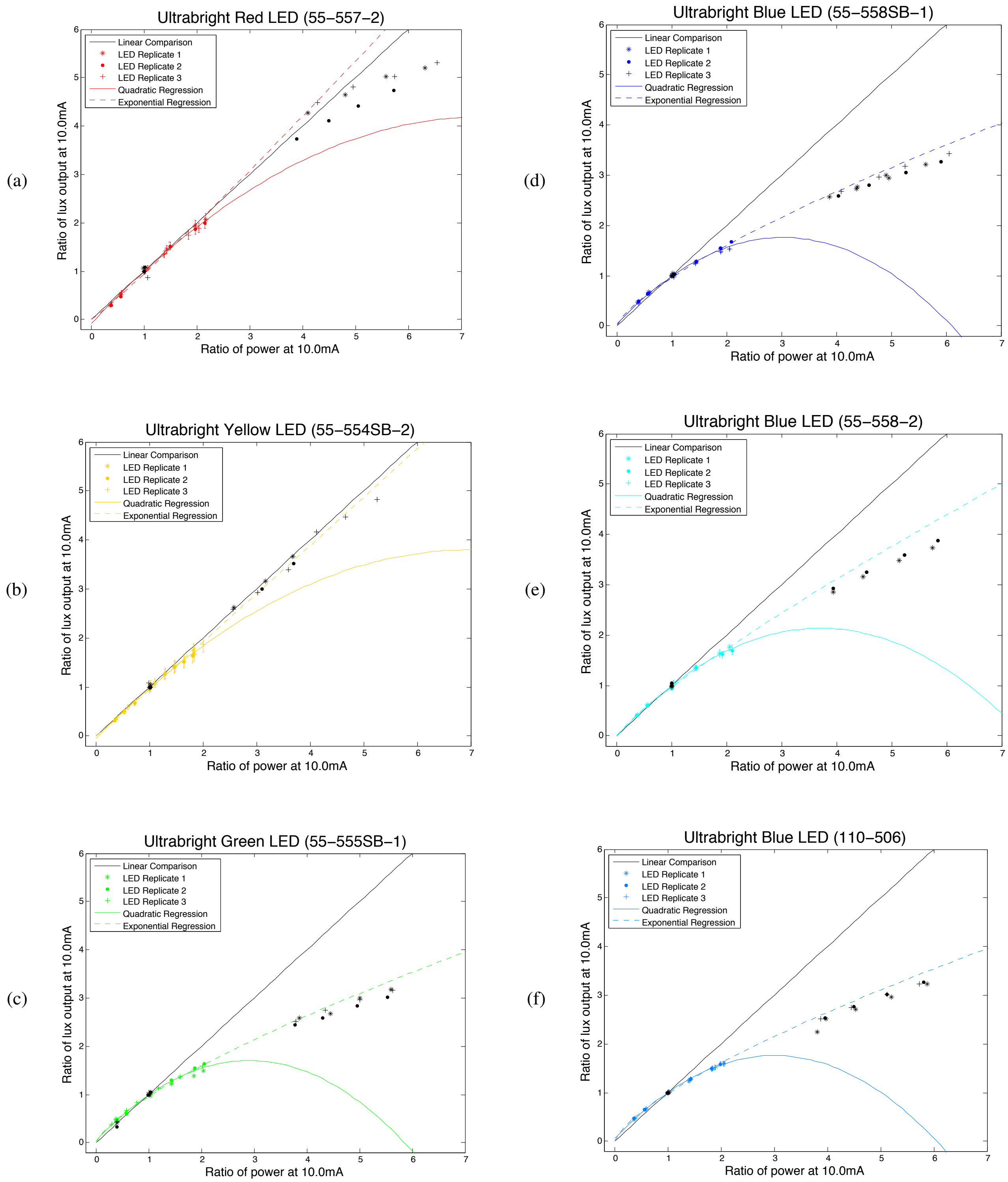


Fig. 5: Efficiency models including the high current data points.