DESIGN OF A 8 CHANNEL DATA ACQUISITION SYSTEM FOR MEASURING DIODE JUNCTION TEMPERATURE

BY
JASON E. MAYNARD

PARTNERED WITH
CHRIS GRASBERGER

ADVISER
DR. JIANBIAO PAN

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CALIFORNIA POLYTECHNIC STATE UNIVERSITY
SAN LUIS OBISPO

Graded by ___________________       Date of Submission _________________

Checked by_____________________       Approved by______________________
ABSTRACT

The solid state lighting industry is striving to expand the use of light emitting diodes (LEDs) in more applications, particularly in high brightness applications. As the power of LEDs increase, heat removal becomes a critical issue. To improve device lifetime, quantum efficiency, and LED colour, the diode p-n junction temperature ($T_j$) must be kept to a minimum. Measuring this key parameter is difficult or impossible with direct methods, such as thermocouples and infrared cameras, due to the small size of LEDs. Fortunately, junction temperature can be measured indirectly by using a relationship between the diode forward voltage ($V_f$) and junction temperature. This allows for measurement of LED junction temperature after initial calibration with a digital multi-meter with an approximately linear equation that relates the forward voltage of the diode to its junction temperature. This senior project is a summary of the design, fabrication and testing of a system that allows for calibration necessary to develop a working equation that can be used to measure junction temperature of a given diode.
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CHAPTER 1: INTRODUCTION

Since their introduction in 1962 (Holonyak & Bevacqua, 1962), research of light emitting diodes (LEDs) has steadily increased, partially because of an increased awareness of their potential applications in a wide range of markets. Applications have expanded to include traffic signals, interior and exterior automotive lighting, including high brightness headlights, large display lighting, LCD TVs, projectors and increasingly in commercial and residential lighting (Kuo, et al., 1990; Steranka, et al., 2002). These potential applications coupled with an increased awareness of the world’s finite energy supply and the need to produce energy efficient electronics has spurred research into alternative lighting technology. The goal of these studies is to address the performance needs of a replacement to conventional lighting which minimizes the environmental impact.

LEDs offer key advantages over conventional lighting such as, long lifespan, decreased environmental impact, energy efficiency and impact resistance (Johnson, 2002; Alan, 2004). These advantages, along with strong support of government, through initiatives such as the L-Prize (a contest with a reward of $10 million dollars to the creator of an LED that meets specific advanced requirements) are fueling exponential expansion of solid state lighting technology (US Department of Energy (a), 2008). With the current rate of advancement, LED lighting technology is suspected to be the dominant lighting source by 2025 (Luo, et al., 2007). This timeline is dependent on addressing the key barriers to LED application in high brightness and pure white applications.

According to the US Department of Energy, solid state lighting (SSL) faces six key barriers to bringing SSL to the forefront in lighting: quantum efficiency, longevity, stability and control, infrastructure, cost reduction and packaging (US Department of Energy (b), 2008). In order to improve the longevity of LED lighting, there must be improved thermal management in LED packaging. This problem is the main obstacle in creating high brightness LED applications. As an LED’s junction temperature increases, the functional lifespan of the LED decreases. In order to test and verify the
performance of LED packages, there must be an accurate measurement technique for obtaining junction temperature.

The key problem in the testing of LED junction temperature is the difficulty to obtaining accurate junction temperature measurements using traditional measurement devices such as thermocouples and infrared imaging. This is partially due to the small size of many of bare LEDs, which are commonly on the order of 100 to 500 micron$^2$. This makes it impossible to attach a thermocouple to the die and very difficult and costly to use thermal imaging that achieves a high enough resolution to accurately measure the diode junction temperature. This problem is compounded by the fact that most thin films used for LED junctions and chip substrates are made from transparent material. For this reason LEDs must be painted black, making them radiating black bodies, in order to be test with thermal imaging. This not only destroys the package, but is not a suitable means of field testing LED packages.

The goal of this project is the design and validation of an 8 channel data acquisition system (DAQ) that allows for measurement of LED package without destruction of the LED package. The need for this testing equipment was encountered on a separate project at Cal Poly, which designed a low-cost thermally efficient package to be used in channel lighting. Thermal modeling has been performed on the package design to estimate the theoretical junction temperature of the diodes, but in order to validate the model, sample temperatures have to be taken from the prototype package.

To address this problem a piece of testing equipment was designed and built based on the forward voltage method. The method measures the junction temperature indirectly by utilizing a relationship between the forward voltage of the diode and the temperature of the $p$-$n$ junction. As the temperature of the junction increases, the forward voltage decreases approximately linearly for a given current. This enables the use of forward voltage as a test statistic to make inferences about the actual temperature of the LED junction while operating at its designed drive current. The 8 channel DAQ was designed to be integrated with a power supply and oven that holds the LED packages at set temperatures in for calibration before field testing. A power supply was built in order to provide an independent power
source. This report contains the background research on thermal testing methods and a summary of the design, testing methods, results and conclusions from the project.
CHAPTER 2: LITERATURE REVIEW

Four methods of thermal testing of the junction temperature were researched: transient thermal testing (forward voltage method), infrared testing with an IR camera, measurement with a thermocouple and computer thermal simulation. The most common approach to thermal testing is the forward voltage method or infrared camera, used in conjunction with a thermal simulation. (Yang, et al., 2008; Sturm, et al., 1998; Luo, et al., 2007; Holonyak & Bevacqua, 1962) These techniques are mainly applied to calculate the junction temperature of the LED chip and the thermal resistance of the die packaging. The majority of methods researched are techniques which are used in R&D applications, but considerations for use in field testing and non-destructive sampling will be considered in selection of a testing method.

2.1 THERMAL MODELING TECHNIQUES

The following is an overview of the thermal modeling software packages and the computations which they perform. Computer simulation is often used in the design of thermal packaging, but often must be coupled with a direct measurement technique in order to verify the results.

2.1.1 COMPUTER THERMAL MODELING

The initial modeling method used for the Cal Poly channel lighting prototype testing was thermal modeling with FloEFD, a thermal modeling package produced by Mentor Graphics (Mentor Graphics: Flomerics, 2009). A literature review of other LED research showed a variety of software packages such as FloTHERM, Fluent, FLUX, SYSTUS and TOCHNOG, all of which were used in LED thermal modeling (Farkas, et al., 2005; Yang, et al., 2008; Yang, et al., 2006; Lan & Shin, 2007). There are many software packages available for thermal modeling, but the core computations are based off of the same mathematical theories and assumptions. Finite element analysis (FEA) is the basis for all of the calculations done in the thermal testing. FEA is mathematical technique for solving partial differential
equations and integrating across finite areas. The solution approach is based either on eliminating the
differential equation completely (steady state problems), or rendering the partial differential equation into
an approximating system of ordinary differential equations, which are then numerically integrated using
standard techniques such as Euler's method, Runge-Kutta, etc (Vivette & Pierre-Arnaud, 1986).

Finite element analysis is a practical method for solving partial differential equations over
complicated domains (such as cars or airplanes), when there are domain changes (such as during a solid
state reactions with moving boundaries), when the desired precision varies over the entire domain, or
when the solution lacks smoothness (Vivette & Pierre-Arnaud, 1986). For measurement of LED
applications this is important because temperatures across the LED package vary greatly and high
resolution is needed in areas that are around the p-n junction. The areas in need of high resolution are
relatively small compared to the size of the entire package and software that uses FEA has the ability to
refine the computational mesh in areas that require enhanced precision.

![Figure 1 FloTherm thermal simulation model (Yang, et al., 2008)](image)

In three reviewed papers that also used the forward voltage method, two different software
packages were used for thermal simulations; FloTHERM and Fluent (Yang, et al., 2006; Luo, et al., 2007;
Yang, et al., 2008). Both packages include a computational fluid dynamics solver, which carries out a full
3D solution of the Navier-Stokes equations. The Navier-Stokes equation can be used for computations of
mass, momentum and energy transfer using the finite element analysis (FEA) (Yang, et al., 2006). When
used for thermal measurement of LEDs, packages are modeled in a 3D computer aided design (CAD)
program, and then the model is transferred to the thermal analysis program. A mesh grid is created either
automatically, manually or by a combination of the two. Applying an appropriate size mesh to the model
is important to achieve the desired resolution in important areas of the model and achieve accurate results. Although it is important to have sufficient resolution in required areas, it is also important to simplify the model to allow timely solving of the model with limited computation power. To abstract the important areas of the model the computed mesh can be viewed and highly detailed areas of the model can be geometrically simplified.

2.2 THERMAL MEASUREMENT TECHNIQUES

The following is an overview of two common thermal measurement techniques. Infrared imaging and forward voltage measurement are the two most commonly used techniques for junction temperature measurement. The methods, pros and cons are considered for each technique. These were considered when determining the best method for measuring the junction temperature of the channel lighting prototype at Cal Poly.

2.2.1 THERMAL INFRARED IMAGING

Infrared (IR) imaging can be used for measurement of diode junction temperature. All objects emit a certain amount of black-body radiation as a function of their temperatures. Generally speaking, the higher an object's temperature, the more infrared radiation as black-body radiation it emits. An IR camera can detect this radiation in a way similar to the way an ordinary camera does visible light. It works even in total darkness because visible light level does not matter. This makes it useful a prominent technique in rescue operations in smoke-filled buildings, facilities projects and underground applications.

Modern cooled detectors operate in the 60 to 100 Kelvin range, depending on type and performance level. Without cooling, the IR sensors would be flooded by their own IR radiation without cooling. The drawbacks of cooled IR cameras are that they are expensive both to produce and to run. Cooling is power-hungry and time-consuming. The camera may need several minutes to cool down before it can begin working. Cooled IR cameras produce greater sensitivity and allow for the use of higher F-number lenses, making high performance long focal length lenses both smaller and cheaper,
which are required for high resolution imaging of LEDs (Wikipedia (a), 2009). Although IR cameras are commonly used in the temperature measurement of electrical components and integrated circuits, they pose problems for LED junction temperature measurement.

![Image of LED package with IR camera](image)

**Figure 2** Thermal image of an LED package using IR camera

The small size of LEDs makes it difficult to obtain accurate measurements of an LED junction. Figure 2 shows the image from a standard IR camera made for facilities purposes and the difficulty in targeting an LED junction that can potentially be smaller than 100 micron$^2$. IR cameras that can achieve high enough resolution and magnification to target small LED junctions cost close to $100,000 making them an infeasible method for Cal Poly’s testing. Additionally, in order to obtain thermal measurements the target must be a black-radiating body. This requires painting of the LED rendering the prototype useless for future use.

### 2.2.2 Forward Voltage Method Measurement

The forward voltage method is the most widely used and accurate way of measuring junction temperature (Xi, et al., 2004). The method uses an LED’s forward voltage, which varies approximately linearly with the junction temperature of the die, to measure the junction temperature indirectly. This method is also the only available method that can obtain measurements within the $p-n$ junction of the LED. The testing process uses an oven to heat or cool the die, then take measurements of the forward voltage of the die at each temperature. This allows the operator to establish an approximately linear
relationship between the forward voltage of the diode at a given temperature and current. The slope of this line, $dV_f/dT$ or K factor can then be used to measure the junction temperature of the diode while it is running at its operating current.

An expression can be derived that takes into account all the contributing factors to the dependence of forward voltage on temperature. The equation begins with the Shockley Ideal Diode equation, which is derived from Navier-Stokes equation. The Shockley Ideal Diode equation or the ideal diode law, which can be seen in Equation 1, is derived with the assumption that the only processes giving rise to current in the diode are due to electrical field, diffusion and thermal recombination-generation. It also assumes that the recombination-generation current in the depletion region is insignificant. This means that the Shockley equation doesn’t account for the processes involved in reverse breakdown and photon-assisted recombination-regeneration. Additionally, it does not describe the “leveling off” of the I–V curve at high forward bias due to internal resistance (Wikipedia (a), 2009).

$$\frac{dV_f}{dT} = \frac{d}{dT} \left[ \left( \frac{n_{\text{ideal}} kT}{e} \right) - \ln \left( \frac{J_f}{J_s} \right) \right]$$

Equation 1 Shockley Ideal Diode Equation (Xi, et al., 2004)

Where $V_f$ is the forward voltage, $J_f$ is the forward current density, $J_s$ is the saturation current density, $n_{\text{ideal}}$ is the diode ideality factor, $k$ is the Boltzmann constant and $T$ is the temperature of the diode junction is Kelvin. The saturation current density depends on the diffusion constants of electrons and holes, the lifetimes of electrons and holes, the effective density of states at the conduction band and valence band edge and band gap energy, all of which depend on the junction temperature (Xi & Schubert, 2004). Substituting the temperature dependencies of these quantities the derivative can yield an equation for the slope of this dependence. The equation for the slope can be seen in Equation 2.

$$\frac{dV_f}{dT} = \frac{eV_f - E_g}{eT} + \frac{1}{e} \frac{dE_g}{dT} - \frac{3k}{e}$$

Equation 2 Forward Voltage and Junction Temperature Relationship (Xi, et al., 2004)
This equation gives the fundamental temperature dependence of the forward voltage and includes the temperature dependence of the energy gap. The first, second, and third summand on the right-hand side of the equation is due to the temperature dependence of the intrinsic carrier concentration, band gap energy, and the effective densities of states \( N_C \) and \( N_V \), respectively.

![Figure 3](image)

**Figure 3 Temperature vs. diode forward voltage (\( V_f \))** (Xi & Schubert, 2004)

Figure 3 shows the approximately linear relationship between the temperature and forward voltage of diode are plotted for several currents. Each current has a unique offset, but the slope or \( dV/dT \) at each current remains approximately the same (Xi & Schubert, 2004). The slope, which is referred to as the K factor is determined by placing the diode in an oven and heating it to a range of interval temperatures. At each temperature the forward voltage of the diode is tested at any input currents of interest. The results can then be plotted and a linear regression can be used to determine a working equation. The equation and slope or K value of this linear regression at each current is then converted into a working equation that can be seen in Equation 3.

\[
T_j = \frac{V_f - \beta}{K \text{Factor}}
\]

**Equation 3 Working Equation for Junction Temperature**
The linear regression equation then defines a relationship between the forward voltage of the diode and the junction temperature that can be used as an indicator in order to determine the operating temperature of the LED at a given drive current. Using forward voltage as a test statistic makes it possible to indirectly measure absolute changes in the temperature of the \( p-n \) junction.

Diode forward voltage is an ideal test statistic to use to measure junction temperature, because it is affected by the flow rate of electrons through the junction. Therefore forward voltage measures a change in temperature that is very close to the \( p-n \) junction. This is unlike a thermocouple or IR camera, which only measure the junction temperature directly on the surface of the diode. Additionally, the cost of the system needed to take measurements of the voltage shifts is far less than the cost of an IR camera with sufficient resolution to measure the temperature of a small diode. For this reason the measurement device designed in this project was based on forward voltage method.
CHAPTER 3: DESIGN

3.1 PROJECT OBJECTIVE

The objective of the design was to create a measurement tool that was capable of obtaining an accurate measurement of the junction temperature of a diode based on the forward voltage method.

3.2 FORWARD VOLTAGE METHOD MEASUREMENT OVERVIEW

The design of the measurement system was based on previously established forward voltage measurement techniques, which are based on the dependency between diode forward voltage and junction temperature. This relationship is overviewed in detail the literature review section of this report. The method works based on an approximately linear relation between the diode voltage and the junction temperature at specific currents. After calibration the data can be used to establish a linear plot of temperature versus forward voltage and establish a linear equation, which can then be used to interpolate the temperature of the diode junction with a known forward voltage and drive current.

Figure 4 Conceptual Model (by Chris Grasberger)

The basic components used in order to measure the junction temperature of an LED junction is a data acquisition board to measure the change in forward voltage, a microcontroller to generate the
required pulses to measure the LED and programming that can provide logic and control of the entire system. The conceptual model that the design was based off of can be seen in Figure 4. A user interface created in LabVIEW, allows the user to initiate a test. The digital signal is then sent from the data acquisition hardware to the microcontroller on the measurement printed circuit board (PCB). The microcontroller sends a digital pulse of preset length, which is converted into an analog pulse that runs through the LED, allowing measurement of its forward voltage and the current under the experimental conditions.

In order to generate the test pulse the microcontroller toggles a test switch between two digital to analog converters (DAC 0 and DAC 1). DAC 0 is set at the nominal voltage of the LED, which runs a small current through the LED while not being tested. DAC 1 is set to the voltage that runs the LED at the current the user wishes to test. The microcontroller switches to DAC 1 for a small time interval, which sends a higher current pulse to an operational amplifier (op-amp), which amplifies the signal. This is necessary because the DACs are not capable of generating large enough voltages to run the LED. After the pulse is amplified it runs through the LED to be tested and then through a resistor of known value and continues to ground.

Two instrument op-amps measure the voltage across the diode and resistor at the sampling rate of the data acquisition system during the pulse. This data is sent back to LabVIEW and processed to determine the forward voltage of the LED and the current. Figure 5 shows a diagram of how the testing module functions.
Figure 5 LED DAQ Circuit Diagram (by Chris Grasberger)
The system uses a data acquisition system made by National Instruments to collect data which is output by the measurement PCB. The system is programmed by LabVIEW, which is loaded on a desktop computer that interfaces between the DAQ and measurement PCB in the main box. The signal from the user is sent from LabVIEW to the data acquisition system which uses a 5V pulse in order to open the analog switch and send the current pulse from DAC 1.

By using small current test pulses a measurement of the forward voltage of the die can be taken without self heating the die. Figure 6 shows the sequence of the analog switch, digital to analog, resistor and LED pulses. The system uses a 4 wire system, which uses 2 wires for small rest current and 2 wires to deliver the test pulse. The 2 drive connections keep the diode at a low constant current between test pulses, which eliminates needing to switch the diode completely on and off, which requires additional time for the LED to “warm up” and reach a steady state forward voltage. The 2 test wires deliver test pulse, which is higher than the rest current while the data is taken.

![Figure 6 Microcontroller Pulse (by Chris Grasberger)](image)

The test pulse is delivered by a microcontroller on the diode measurement PCB, which has a small delay in order to allow LabVIEW to switch from sending the test signal to data collection mode. After the small delay the microcontroller sends a programmable number of test pulses to the selected diode and LabVIEW records a programmable number of data points during the pulse for the voltage of both the diode and resistor to measure the current.
The concept for the board measurement tool is based on previously tested theory about the relationship between diode junction temperature and forward voltage. The logic design which the testing board was based on has also been established in previous research (Xi & Schubert, 2004). Therefore, the design of the testing equipment was based around integrating a new PCB that would handle the powering and testing of the LEDs with a National Instruments data acquisition system (DAQ). The data sheet for the National Instruments Data Acquisition System can be seen in Appendix E. The port outputs for the two boards screw terminals can be seen in Figure 26 in Appendix C. The system uses an independent power supply in order to provide the required positive 12V, negative 12V and ground to the measurement system. Details of the power supply can be seen in section 3.3.2 Power Supply Design.

3.3 PHYSICAL DESIGN

3.3.1 PRINTED CIRCUIT BOARD DESIGN

There are three PCBs used within the DAQ, two of which are parts of the National Instruments (NI) Data Acquisition system. The digital signals are confined to one National Instruments board and the analog signals are confined to the other NI board. The measurement PCB was fabricated by Advanced Electronics Incorporated (Advanced Circuits, 2007).

The board that was designed to handle the measurement of the LEDs and resistors was designed using the PCB design software, DipTrace, which has a limited access version that can be downloaded for free (DipTrace, 2009). The diode junction measurement board went through several iterations before a final design was fabricated and assembled. Small problems were fixed using external wiring connections across the surface of the board rather than fabricating a new board, due to the high cost of manufacturing a new board and replacing its components. The board is split into 4 main sections, resistor selection, LED selection, LED and resistor measurement and interfacing to the National Instruments DAQ. The schematics for the board along with the circuit diagram can be found in Figure 22 in Appendix B. The board has eight DIN 5 female inputs where up to eight LEDs can be connected. The positive and negative
connections for the rest and drive current are connected from the outside of the main box to these ports. The pin allocation for the DIN 5 connections can be seen in Figure 24 in Appendix B.

The board was designed with a microcontroller that would handle the pulsing of the LEDs, because of its ability to send extremely short pulses to the LED, while freeing the LabVIEW software to perform data collection. The microcontroller sends the test pulse to the LED by switching an analog switch from letting the resting voltage set by DAC 0 (digital to analog converter) to DAC 1 which is set at the predetermined testing voltages. The analog switch is activated for a programmable length of time, which defines the pulse length. This pulse length is set to be long enough to allow for the current to reach steady state and sufficient amount of samples to be taken, but not so long that the LED junction temperature begins to be affected by the change in current. The measurement board diagram made on DipTrace can be seen in Figure 20 and Figure 21 in Appendix B. The bill of materials (BOM) for the measurement board can be seen in Table 1 in Appendix B.

3.3.2 Power Supply Design

The DAQ required an independent positive and negative twelve volt power source. A Dell power supply was converted by expanding the casing and adding a resistor with a heat sink and power switch. An LED was also added to give the user a visual cue of the on/off status. The positive, negative and ground were wired to a DIN 5 male connector. The pin allocation for the power cord can be seen in Figure 25 in Appendix B.

3.3.3 Casing Design

The casing was designed on SolidWorks using its sheet metal design function, prior to fabrication (Dassault Systèmes SolidWorks Corp, 2009). It was designed to permanently hold the three PCBs; two National Instruments DAQs and the measurement PCB in the core, while allowing access to both sides of the measurement board from the top and bottom. The additional access was needed in order to allow for wiring, troubleshooting and modification of the board without removing it from the casing, which could
potentially damage it. The casing is grounded, which allows for handling of the board without the risk of electro static discharge (ESD) damage to the components. The measurement PCB was placed horizontally to enable soldering on both sides of the board and access to the microprocessor reset switch as can be seen in Figure 14 in Appendix A. The two National Instruments boards were placed vertically on the walls, allowing access to the one side where wires would be connected to the screw terminals as can be seen in Figure 13 in Appendix A.

The casing was designed to incorporate the three large heat sinks on the measurement PCB and provide ample room to run wiring to between the three PCBs and house the fuse box as can be seen in Figure 14 in Appendix A. The DAQ and the power supply were kept as separate entities, so new casing had to be made for the power supply that incorporated the power connection, power display LED and power switch which can be seen in Figure 9 in Appendix A.

The casings were fabricated out of 10 gauge sheet metal. The main box, seen in Figure 11 in Appendix A, was fabricated in three separate pieces; the core, top lid and bottom lid. The blank sheets were cut to size specified by the blueprints output by the SolidWorks sheet metal function. All cuts were performed on a vertical pneumatic shear. The locations of bends were measured out and scribed on the insides of the sheet metal. A total of thirteen holes were punched in the main body to allow for the electrical connections. Eight ½ inch holes were punched for the LED DIN 5 input/output connections. Two ¼ inch holes were punched; in order to mount two LEDs to signal that the power was being received from the positive and negative 12V power supply, as can be seen in Figure 9 in Appendix A. Two custom holes were punched in the rear of the box with a pneumatic die punch, where the NI DAQ connection plugs would protrude. A ½ inch hole for the mountable DIN 5 power cable connection was punched in the center. After the casing had been bent two additional ½ inch holes were drilled with a step drill in order to allow for changing of two fuses. The connections on the rear of the casing can be seen in Figure 10 in Appendix A.
The casing for the power supply was also fabricated from 10 gauge sheet metal and air vents were punched in the front of the casing to allow for flow from the fan to cool the resistor heat sink. Holes were punched to create openings for the outgoing power cord, power switch and standby LED light. A mounting bracket to hold the resistor and heat sink was fabricated and fastened to the front wall of the casing by a resistance spot weld.

The bending of the sheet metal was done on a press break. In order to achieve the required shape the flanges were bent prior to forming the box. The box shape was formed last and the dimensions were measured in order to ensure proper fit of the circuit boards. The box was welded in place along the vertical flange with a resistance spot welder. Sheet metal tabs were also spot welded into areas where holes for the PCB mounting holes would be drilled. This allowed for counter-sunk holes to be drilled and the lids to sit flush against the top and bottom of the core, which can be seen in Figure 15 in Appendix A.

The mounting holes for the PCBs were then drilled and counter-sunk. The holes to fasten the lids with sheet metal screws were also drilled on the flanges of the lids. The mounting holes for the power supply casing were also drilled and counter-sunk. The entire system was assembled with the mounting hardware and appropriate spacers to ensure a proper fit. After final adjustments were made, the entire casing was sandblasted, primed and painted.

3.4 PROGRAMMING DESIGN

3.3.1 MICROCONTROLLER PROGRAMMING

Programming of the microcontroller was written in C++. The program for the microcontroller was separated into four modules; \textit{avr\_DAC8831\_driver}, \textit{interface\_handler}, \textit{avr\_serial} and \textit{run} code files. Each were programmed onto the microcontroller through a serial input port mounted on the measurement board onto an 8-bit ATMEL AVR microcontroller with 16/32/64K bytes in-system programmable flash. The data sheet for the microcontroller can be found in Appendix D.
The first program, `avr_DAC8831_driver`, controls the data being sent to the digital to analog converters (DACs). It takes in an unsigned integer and an unsigned character and together they designate which DAC to send the integer to and the integer designates the voltage to be sent to the DAC. This function allows the interface from the calling class to this class. It accepts both the value for the DAC and the target DAC to be programmed.

The second program, `interface_handler`, is the interface program used to handle the signals between the hardware on the circuit board and the external controller, which in this case is LabVIEW. The module allows for data transfer to the microcontroller to store new values, and it also allows the external controller to send a pulse to the test LED. A small delay between the signals from the external controller allows for the external controller to switch into a data collection mode before the LED receives the test pulse and data is collected. The module sends data from the microcontroller to the external controller, which collects the data. The program triggers on both high and low transitions, but performs separate functions. It ignores the low to high transition since that is when data is clocked in to the DAC. On high to low transitions it sets the pins for the next bit of serial data to be received.

The `avr_serial` program contains the functions which allow the use of a serial input port on an AVR microcontroller. Compatibility macros allow the module to isolate the names of various registers from the many specific AVR device types. This code is designed to work for low-performance applications without requiring the use of interrupts which means that it is reliant on the external clock for signals on changes in execution. Interrupt based receiving code has not been completed or tested.

### 3.4.2 LabVIEW Programming

The external controller used LabVIEW, which is a graphical programming environment used by to develop measurement, test, and control systems using intuitive graphical icons and wires that resemble a flowchart. LabVIEW integrates directly with the National Instruments PCI-6254 DAQ. The user interface was separated into four tabs; test, bundled data, mid-level interface and settings.
The main interface or *test* tab allows the user to set the basic setting and perform a test run. The user can select to use one of four resistors; 0.3Ω, 10Ω, 100Ω or 1kΩ. The resistor should be selected based on the designed operating current of the LED and the desired resolution for the test. Next the user can select which of the eight LEDs will be tested. The user then selects the rest and test voltage for the LED. The rest voltage is the voltage output by DAC 0 and sets the resting voltage that the LED will be held at between test runs. This voltage should be slightly higher than the nominal voltage of the LED in order to produce the minimum current to turn on the LED. The user then selects the test voltage, which is the voltage output by DAC 1 and sets the voltage that the LED will be at during the test pulse. This voltage should be set to run the LED at its intended drive currents. Once these settings are complete the device ready to collect data.

LabVIEW is used to send the run signal to the microcontroller, then switch into data collection mode and record the forward voltage, test current, oven temperature and sample number during the subsequent test pulse. The data is then arranged into an array and within LabVIEW and subsequent samples stacked in a single column below the subsequent sets. Once testing at the desired treatment is complete the user can select to “Bundle Data” which moves the set into a holding spreadsheet Figure 17 in Appendix A. Once the data collection run is finished the file can be exported into Microsoft Excel® or another spreadsheet program, where further analysis of the data can be performed. The data flow diagram can be seen in Figure 7.
The *mid-level interface*, which can be seen in Figure 18 in Appendix A, is only used to troubleshoot any problems and displays the values and status of terminals on the measurement board.

The *settings* tab, which can be seen in Figure 19 in Appendix A, is used to change some of the default test settings. A description of each of the settings can be seen below.

Settings Tab:

- **Pulse time**: Sets the length of test pulse in microseconds
- **Data delay**: Sets the delay in microseconds between initiating test pulse through LabVIEW and first test pulse
- **Acquire timeout**: Time in seconds without a completed test before LabVIEW registers that an error has occurred
- **Number of samples**: Sets the number of samples to be taken during pulse (this is limited by the maximum sampling rate of the data acquisition system)
- **DAC error tolerance**: Sets the voltage tolerance for the DAC

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*Figure 7 Data Collection and Storage Model*
3.4.3 Testing Example

The following is an example of the steps taken by a user in order to setup a data collection run through the test tab in the LabVIEW interface:

1. Set DAC 0 to a voltage slightly higher than LED nominal voltage so a minimal amount of current flows
2. Set DAC 1 to a higher voltage that drives the test LED at the desired current for the pulse
3. Select test resistor (0.3, 10, 100, 1k ohm)
4. Select LED to test (1 through 8)
5. Press Collect Data. Each consecutive press will collect an additional set of data at given conditions and add it to the active column
6. To test another configuration, press “Collect next set” to temporarily store the collected data in the bundled data tab and begin collecting next set of data under new treatment conditions
CHAPTER 4: TESTING AND VERIFICATION METHODS

Partial testing of the DAQ was performed periodically through assembly of the DAQ using a digital multi-meter. The measurement PCB required many surface mount and through-hole solder joints, which required manual testing. Additionally, board-to-board wire interconnects were tested in order to ensure proper connections. These connections were tested with a digital multi-meter in order to ensure proper electrical connections were established. The voltages of the electrical components were tested to ensure the programming and components were functioning correctly. This was especially important for the DACs, which would establish the rest and test currents for the LEDs.

The initial trial runs were performed in the electronics manufacturing lab at Cal Poly, on a generation one red LED. The LED was directly mounted onto a 4 wire twisted pair cable with shielding. A DIN 5 male connector was fitted to the other end of the wire. For the tests a Tenney Engineering T20C-SPL mechanical convection oven was used (Tenney Engineering Incorporated: Thermal Product Solutions, 2009). The oven has both heating and cooling elements, which allow for measurement of temperatures above and below ambient temperature. The LED was placed in the center of the oven and a thermocouple attached to a digital multi-meter was placed directly beside it. The thermocouple allowed for accurate measurements of the oven temperature at a point that was in close proximity to the LED. A diagram of the test setup can be seen in Figure 8.
The temperatures tested were 60, 45, 30, 15 and 0°C and the drive current was set to 5mA and 35mA for the 10Ω and 100Ω resistor, respectively. The initial samples taken contain 550 data points taken over 0.5 milliseconds. At each tested temperature 10 runs of 550 data points were collected at a resistor value of 10Ω and 100Ω. The oven took several minutes time to reach a constant temperature because of the heat radiated off of the large amount of insulation. It was assumed that once the oven reached steady state the LED junction would be the same temperature as the temperature of the thermocouple positioned beside it.

At the beginning of each test the temperature reading was recorded off of the multi-meter and 10 sample runs were collected in sequence. The data was then bundled and moved to the temporary spreadsheet within LabVIEW. The oven was then set to the next temperature interval, in descending order; from 60°C to 0°C.

Once all of the data was collected the spreadsheet was exported to Microsoft Excel. The data values for each of the 10 sample runs were averaged together to create an average for each of the 550 samples taken at each treatment level. The points for the forward voltage of the LED and the corresponding current were then plotted in a graph. A regression line was fit to the data in order to test whether the LED was not being heated by the test pulse. If there was a significant slope to the line then it would indicate that the temperature of the die was changing over the pulse duration. The current has a
short transient period and does not immediately reach steady state. Therefore, the first 200 points before steady state is reached were removed from the data set.

Minitab, a statistical analysis package was used to perform regression analysis on the data (Minitab Incorporated, 2009). Minitab was used to generate an analysis of variance (ANOVA), coefficient of determination ($R^2$) and generate confidence intervals for the slope and intercept values of the regression line. The y-intercept of the regression equation is used to verify that the die was not being over heated during the test pulse. The confidence intervals for the y-intercept allow for a measurement of the error in the initial temperature.

A test of hypothesis was performed on the regression equation in order to verify the underlying forward voltage theory. The test shows that the slope of the equation is significantly affected by the forward voltage test-statistic. The decision rule was based on an F-statistic calculated from the averaged data. The hypothesis is shown below.

**Validity of Regression Model Hypothesis:**

$H_0$: $\beta = 0$

$H_A$: $\beta \neq 0$

**Decision Rule:** Reject null hypothesis if ($F_{\text{statistic}} > F_{\text{critical}}$)

A second test of hypothesis was used in order to verify both the constant and slope generated by temperature change contributed significantly to the regression model. A decision rule was based on a t-statistic. The hypotheses are shown below.

**Contribution of the Constant to Regression Model Hypothesis:**

$H_0$: $\beta_0 = 0$

$H_A$: $\beta_0 \neq 0$

**Contribution of the Temperature Variable to the Regression Model Hypothesis:**

$H_0$: $\beta_1 = 0$

$H_A$: $\beta_1 \neq 0$

**Decision Rule:** Reject null hypothesis if ($|t_{\text{statistic}}| > t_{\text{critical}}$)
To test that the system is achieving correct values for a given LED, data from Chris Grasberger’s initial master’s thesis research was used. The tests used eight Philips LumiLEDS LUXEON Rebel packaged LEDs mounted on a test PCB (Philips LumiLEDs, 2009). The LEDs were tested at drive currents of 20, 100, 350 and 700mA and temperatures of 0, 20, 40, 60, 80 and 100°C. Data was collected off of four test boards and the average of the tests were input into Minitab to evaluate the linearity of the regression equation, coefficient of determination and confidence and prediction intervals for the regression equation. The values obtained from the measurement DAQ for $dV_f/dT$ were verified by comparing the measured values to the reported values published by Philips LumiLEDs for the LUXEON Rebel LED package.
CHAPTER 5: RESULTS

The initial trial runs were performed with a standard 1st generation red through-hole LED. The LED was placed in the oven along with a thermocouple. The LED was tested at 60, 45, 15 and 0°C. Ten sets of 550 samples were taken at each temperature at resistor values of 10 Ω and 100Ω current, which correlate to a current of 5mA and 35mA, respectively. A regression equation was generated with the average sample points taken. A test of hypothesis showed that the regression equation has a very strong linear relationship between the temperature of the junction and the forward voltage of the diode. Based on the results of the ANOVA the null hypothesis was rejected (F = 13014, P = 0.0) as can be seen in Table 2 in Appendix C. Therefore, temperature is a significant linear predictor of forward voltage in the regression model. The second test of hypothesis for the significance of the predictors within the regression model was performed. The null hypothesis was rejected for the constant (t = 2976, P = 0.0) and temperature variable (t= -114, P = 0.0). Therefore, β₀ and β₁ do not equal zero and the constant and the variable depending on Temperature were found to contribute significantly to the regression model. These values can be found in the Minitab output in Table 2 in Appendix C.

The digital to analog converter (DAC) had a ramp up time of approximately 200microseconds, so first 200 data points from each set were disregarded. Only the data after the test has reached steady state was used to evaluate the heating of the diode, so the first 200 data points were disregarded for all of the samples used in the average. In order to verify that the die was not being heated during the pulse the slope of the line should be close to 0 because if the diode was being heated by the pulse the forward voltage would decrease during the duration of the pulse. The linear fit regression equation shows a slope of virtually 0, which indicates that there is very little self heating of the die from the test pulse.

The graphical plot with the first 200 points removed can be seen in Figure 28 in Appendix C. A linear trend line was then fitted to the data in order to obtain the y-intercept and determine the forward voltage at the beginning of the pulse, which correlates to the initial temperature. The value for the y-
intercept for the regression equation at a drive current of 5mA is 1.96V with a 95% confidence interval of (1.94907V, 1.95564V). The confidence interval output from Minitab can be seen in Table 3 in Appendix C. This correlates to a temperature range of (.035°C, 3.9°C) for a measured value of 1.93°C. After all of the temperatures were recorded a sample point was created for each temperature. The temperature plotted versus the forward voltage can be seen in Figure 29 in Appendix C. A linear trend line was fitted to this data and the slope of the linear fit was recorded as the K value for that LED.

In Figure 28 in Appendix C, it can be seen from the regression line that the linear fit of the 5mA and 35mA pulse has a slope of 0. This shows that there is no significant heating of the die over the 0.5 millisecond pulse, therefore the pulse length was short enough not to significantly heat the die, but long enough for the DAC to reach a steady state current and take a sufficient amount of sample data. From the linear regression equation that can be seen in Figure 29 in Appendix C, $V=K*T+b$, the junction temperature within any packaging or environment can be calculated. For the 1st generation LED the regression equation can be seen in Equation 4 and the working equation to calculate temperature can be seen in Equation 5.

$$V = -0.0017T + 1.9557$$

**Equation 4 Regression Equation for 1st Generation LED at 5mA**

$$T = 1140.41 - 588.24V$$

**Equation 5 Working Equation for 1st Generation LED at 5mA**

Where:

$T$ = *Temperature of the diode junction in Celsius*

$V$ = *Forward voltage of the diode in Volts*

A linear relationship is established from the averaged data taken from the five tests taken at a current of 5mA. The experimental K factor is $dV_f/dT= -0.0017V/°C$ for the 1st generation LED. This coefficient is within reasonable range and the reason for discrepancy between the two test currents was
because of small shifts in the temperature of the oven between testing at the first resistor value of 10Ω and
the second resistor value of 100Ω, thus giving a lower coefficient value for the 35mA tests.

To test the accuracy of the values obtained, LUXEON Rebel LEDs were used to compare the values of
$dV_f/dT$ or the K factor to published values. The regression equation obtained for the LUXEON Rebel at
350mA can be seen in Equation 6. The working equation for the calculation of junction temperature can
be seen in Equation 7 and the fitted line plot with 95% confidence and prediction intervals for
temperature can be seen in Figure 32 in Appendix C.

\[ V = -0.0030 \times T + 3.4253 \]

Equation 6 Regression Equation for LUXEON Rebel LED at 350 mA

\[ T = 1281 - 474.4V \]

Equation 7 Working Equation for LUXEON Rebel LED at 350mA

The K factor generated from the linear regression at 350mA is $dV_f/dT = -3.0mV$ which can be
seen in Figure 31 in Appendix C. The published value from LUXEON is $dV_f/dT = -3.0mV$, which can be
seen in Table 4 in Appendix C. This verifies that the values obtained for $dV_f/dT$ by the data acquisition
system are valid.
CHAPTER 6: CONCLUSION

The 8 channel DAQ was fabricated and assembled successfully. The initial tests were conducted and verified that the DAQ performed as intended and the forward voltage theory held true. A K factor was obtained for two LEDs and a linear regression equation was calculated. This relationship was found for six test currents, using two types of LEDs. From this regression equation a working equation that can be used to interpolate the junction temperature was found. The testing verified that the diode was not being significantly self-heated during the test pulse at low currents.

An approximately linear relation between the junction temperature and the forward current was found. The linear temperature/voltage dependency theory was verified to be highly accurate. Therefore, the forward voltage method technique can be used as a simple and effective means of obtaining the junction temperature of a p-n junction diode. Additionally, the technique was found to be superior to other measurement techniques such as IR cameras and thermocouples because it does not require that the package be destroyed in order to do testing. An additional benefit is that the testing can be done while the package is being used in the field without removal from its installed location. Only measurement of the LED’s forward voltage with a multi-meter is needed to obtain junction temperature data with calibration data taken on the same design of LED. Unlike thermocouples, which require that a probe be soldered onto the LED or close to the package the forward voltage measurement system allows for a lens, casing, encapsulation or surrounding obstructions to stay in place. This allows for more accurate measuring of the junction temperature in a packages working environment.

The use of forward voltage method as a test statistic is powerful for measurement because it is highly correlated to the temperature of the light-emitting junction of the diode. The forward voltage is affected by the increased activity of the electrons at higher temperatures within the p-n junction as the junction temperature increases. Thermocouple or IR cameras can only take measurement at the surface of the diode, while the forward voltage method measures the temperature within the diode junction.
Improvements to the testing equipment are considered next. The design of the testing equipment used a constant voltage driver as opposed to a constant current driver. This makes it difficult to obtain control the current through the LED and therefore makes it difficult to test at precise current values. The board was modified to run as a constant current driver by removing DAC 0 and using DAC 1 to control the forward current. This eliminated the capability of the measurement system to test at a pulse below the resting current, but made it possible to obtain more exact current values.

Continued research found that although there was no significant self-heating of the die at low currents (i < 500mA), as the current used increased, that there are significant increases in the diode temperature during the pulse. This requires that the length of the pulse be shortened, in order to decrease the energy transferred to the die. This also requires a faster sampling rate, which would require a new data acquisition system with a faster sampling rate. Additionally, as the pulse length decreases the “warm up” time of the DACs would become prohibitive. Therefore, system is capable of testing LEDs at low currents, but increased error is introduced as the drive current increases.

Finally, the cost of building the diode measurement system was compared to the cost of purchasing a commercial junction temperature measurement device. Vektrex sells a line of diode testing equipment and a junction temperature measurement device (Vektrex, 2009). The system includes a voltmeter, current source and analytical software. The full details can be found in the measurement device data sheet in Appendix F. Vektrex sales staff estimated that the cost of the system for an educational institution where it would be used for research would be $10,000. The junction temperature device described in this paper was built for $6,196, which includes the board components, PCB fabrication, LabVIEW software, National Instruments data acquisition system and labour costs of the design team. This equates to a savings of approximately $3,800 to Cal Poly for the diode measurement system.
BIBLIOGRAPHY


**APPENDIX A**

- **Main Control Box**
  - 2 National Instrument DAQ boards
  - Logic and Microcontroller PCB

- **Power Supply**
  - (+12V, 0V, -12V)

- **8 LED Connections**
  - (DIN 5 Connections)

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**Figure 9 Power Supply and Measurement Box**

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- **A & B National Instruments DAQ Connections**
  - (NI Custom Plugs)

- **1/2 Amp Fuses**
  - (+12V, -12V)

- **Power Supply Connection**
  - (DIN 5 Connection)

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**Figure 10 Rear View of Measurement Box**
Figure 11 Complete System

Figure 12 Front of Measurement Box
Figure 13 Top View of National Instruments Board A

Figure 14 Top View (Reset switch circled)
Figure 15 Top of Diode Measurement PCB Mounted in Casing

Figure 16 LabVIEW Interface Test Tab
Figure 17 LabVIEW Interface Data Collection Tab
Figure 18 LabVIEW Interface Mid-Level Debugging Tab
Figure 19 LabVIEW Interface Settings Tab
Appendix B

Figure 20 Diode Junction Meter Schematic (Top)
Figure 21 Diode Junction Meter Schematic (Bottom)
Figure 22 Diode Junction Meter Circuit Diagram
APPENDIX C

Figure 23 LED DAQ connections (by Chris Grasberger)
Figure 24 Male DIN 5 LED Connector

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Figure 25 Male DIN 5 Power Connector

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<td>330</td>
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<tr>
<td>26</td>
<td>C39</td>
<td>0.1uF</td>
<td>CAP_0805</td>
<td>2</td>
<td>1</td>
<td>107</td>
<td>R6</td>
<td>2k</td>
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<td>27</td>
<td>C4</td>
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<td>108</td>
<td>R7</td>
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<td>28</td>
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<td>2</td>
<td>1</td>
<td>109</td>
<td>R71</td>
<td>1k</td>
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<td>29</td>
<td>C41</td>
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<td>110</td>
<td>R8</td>
<td>Bypass</td>
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<td>1</td>
<td>111</td>
<td>R81</td>
<td>NC</td>
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<td>1</td>
<td>113</td>
<td>U1</td>
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<td>C45</td>
<td>10uF</td>
<td>CAP_0805</td>
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<td>1</td>
<td>114</td>
<td>U10</td>
<td>Ref5V</td>
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<td>34</td>
<td>C46</td>
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<td>CAP_0805</td>
<td>2</td>
<td>1</td>
<td>115</td>
<td>U11</td>
<td>A-5V</td>
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<td>35</td>
<td>C47</td>
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<td>CAP_0805</td>
<td>2</td>
<td>1</td>
<td>116</td>
<td>U12</td>
<td>8V</td>
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<td>C48</td>
<td>0.1uF</td>
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<td>1</td>
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<td>U13</td>
<td>uC5V</td>
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<td>38</td>
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<td>1</td>
<td>120</td>
<td>U16</td>
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<td>C58</td>
<td>0.1uF</td>
<td>CAP_0805</td>
<td>2</td>
<td>1</td>
<td>121</td>
<td>U17</td>
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<td>C59</td>
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<td>CAP_0805</td>
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<td>C6</td>
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<td>CAP_0805</td>
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<td>1</td>
<td>123</td>
<td>U19</td>
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<td>C60</td>
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<td>CAP_0805</td>
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<td>44</td>
<td>C61</td>
<td>10uF</td>
<td>CAP_0805</td>
<td>2</td>
<td>1</td>
<td>125</td>
<td>U20</td>
<td>relaymux</td>
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</table>

Table 1 Measurement PCB BOM
Figure 27 Initial Sample Test Run Graph for 1st Generation LED
Figure 28 Linear Fit of Data for 1st Generation LED with 1st 200 points removed at 5mA and 35mA

Figure 29 Regression Plot of Initial Trial Data for 1st Generation LED at 5mA
Regression Analysis: Forward Voltage (Vf) versus Temperature (C)

The regression equation is
Forward Voltage (Vf) = 1.96 - 0.00169 Temperature (C)

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Coef</th>
<th>SE Coef</th>
<th>T</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>1.9563</td>
<td>0.00066</td>
<td>2976.51</td>
<td>0.000</td>
</tr>
<tr>
<td>Temperature (C)</td>
<td>-0.00169283</td>
<td>0.00001484</td>
<td>-114.08</td>
<td>0.000</td>
</tr>
</tbody>
</table>

$S = 0.000702846$  $R$-Sqrt = 100.0%  $R$-Sqrt(adj) = 100.0%

Analysis of Variance

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
<th>P</th>
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<tr>
<td>Regression</td>
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<td>0.0064286</td>
<td>0.0064286</td>
<td>13013.53</td>
<td>0.000</td>
</tr>
<tr>
<td>Residual Error</td>
<td>3</td>
<td>0.00000015</td>
<td>0.00000015</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>4</td>
<td>0.0064301</td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

Table 2 Regression Analysis for Initial Test of 1st Generation LED at 5mA
Table 3 Confidence and Prediction Intervals for Intercept of Linear Regression of 1st Generation LED

<table>
<thead>
<tr>
<th>New Obs</th>
<th>Fit</th>
<th>SE Fit</th>
<th>95% CI</th>
<th>95% PI</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.95235</td>
<td>0.00076</td>
<td>(1.94907, 1.95564)</td>
<td>(1.94747, 1.95724)</td>
</tr>
</tbody>
</table>

Figure 31 Linear Regressions of Initial Test of LUXEON Rebel LED
Table 4 LUXEON Rebel LED Data Sheet with the Relevant K factor Circled (Philips LumiLEDs, 2009)

<table>
<thead>
<tr>
<th>Color</th>
<th>Min.</th>
<th>Typ.</th>
<th>Max.</th>
<th>R&lt;sub&gt;0&lt;/sub&gt;</th>
<th>ΔV&lt;sub&gt;f&lt;/sub&gt;/ΔT&lt;sub&gt;T&lt;/sub&gt;</th>
<th>R&lt;sub&gt;BJ&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cool-White</td>
<td>2.55</td>
<td>3.15</td>
<td>3.99</td>
<td>0.3</td>
<td>-3.0</td>
<td>10</td>
</tr>
<tr>
<td>Neutral-White</td>
<td>2.55</td>
<td>3.15</td>
<td>3.99</td>
<td>0.3</td>
<td>-3.0</td>
<td>10</td>
</tr>
<tr>
<td>Warm-White</td>
<td>2.55</td>
<td>3.15</td>
<td>3.99</td>
<td>0.3</td>
<td>-3.0</td>
<td>10</td>
</tr>
<tr>
<td>Green</td>
<td>2.55</td>
<td>3.15</td>
<td>3.99</td>
<td>0.3</td>
<td>-6.0</td>
<td>10</td>
</tr>
</tbody>
</table>

Figure 32 Fitted Line Plot for Averaged Data from LUXEON Rebel LED at 30mA

\[ T = 1281 - 457.4 \cdot V \]

<table>
<thead>
<tr>
<th>S</th>
<th>0.614253</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-Sq</td>
<td>100.0%</td>
</tr>
<tr>
<td>R-Sq(adj)</td>
<td>100.0%</td>
</tr>
</tbody>
</table>
APPENDIX E

8-bit ATMEL AVR Microcontroller with 16/32/64K Bytes In-System Programmable Flash

Features
• High-performance, Low-power AVR® 8-bit Microcontroller
• Advanced RISC Architecture
  - 131 Powerful Instructions - Most Single-clock Cycle Execution
  - 32 x 8 General Purpose Working Registers
  - Fully Static Operation
  - Up to 36 MIPS Throughput at 30 MHz
• On-chip 2-cycle Multiplier
• High Endurance Non-volatile Memory segments
  - 16/32/64K Bytes of In-System Self-programmable Flash program memory
  - 512/2K/4K Byte EEPROM
  - 1/2K byte Internal SRAM
  - Write/Erase Cycles: 10,000 Flash/100,000 EEPROM
  - Data retention: 20 years at 85°C (10 years at 25°C)
  - Optional Boot Code Section with Independent Lock Bits
  - In System Programming by On-chip Boot Program
  - True Read-While-Write Operation
  - Programming Lock for Software Security
• JTAG (IEEE std. 1149.1 Compliant) Interface
  - Boundary-scan Capabilities According to the JTAG Standard
  - Extensive On-chip Debug Support
  - Programming of Flash, EEPROM, Fuses, and Lock Bits through the JTAG Interface
• Peripheral Features
  - Two 8-bit Timer/Counters with Separate Prescalers and Compare Modes
  - One 16-bit Timer/Counter with Separate Prescaler, Capture Mode, and Capture Mode
  - Real Time Counter with Separate Oscillator
  - Six PWM Channels
  - 8-channel, 10-bit ADC
    - Differential mode with selectable gain at 1x, 1.25x or 2x
    - 8x-oriented Two-wire Serial Interface
    - Two Programmable Serial USART
  - Master/Slave SPI Serial Interface
  - Programmable Watchdog Timer with Separate On-chip Oscillator
  - On-chip Analog Comparator
  - Interrupt and Wake-up on Pin Change
• Special Microcontroller Features
  - Power-on Reset and Programmable Brown-out Detection
  - Internal Calibrated RC Oscillator
  - External and Internal Interrupt Sources
  - Six Sleep Modes: Idle, ADC Noise Reduction, Power-save, Power-down, Standby and Extended Standby
• I/O and Packages
  - 32 Programmable I/O lines
  - 40-pin PDIP, 44-lead TQFP, 44-pad QFN/SONMLF (ATmega164P/324P/644PV)
  - 44-pad DRQFN (ATmega164PV)
• Operating Voltages
  - 1.8 - 5.5 V for ATmega164P/324P/644PV
  - 2.7 - 5.5 V for ATmega164PV/324PV
• Speed Grades
  - ATmega164P/324PV/644PV: 0 - 1 MHz @ 1.8 - 5.5V, 0 - 10 MHz @ 2.7 - 5.5V
  - ATmega164P/324PV: 0 - 1 MHz @ 2.7 - 5.5V, 0 - 20 MHz @ 1.8 - 5.5V
  - Power Consumption at 1 MHz, 1.8V, 25°C for ATmega164P/324PV/644PV
    - Active: 6.4 mA
    - Power-down Mode: <1μA
    - Power-save Mode: 0.6μA (including 32 kHz RTC)

Note: 1. See "Data Heteron" on page 8.

See also AVR manual.
APPENDIX F

National Instruments M Series Data Acquisition System

NI PCI-6254

16-Bit, 1 MS/s (Multichannel), 1.25 MS/s (1-Channel), 32 Analog Inputs

- 48 digital I/O; 32-bit counters; analog and digital triggering
- Correlated DIO (32 clocked lines, 10 MHz)
- NI-MCal calibration technology for increased measurement accuracy
- NIST-traceable calibration certificate and more than 70 signal conditioning options
- Get improved measurement accuracy, resolution, and sensitivity by choosing high-accuracy M Series.
- NI-DAQmx driver software and NI LabVIEW SignalExpress LE interactive data-logging software

Overview

The National Instruments PCI-6254 is a high-speed multifunction M Series data acquisition (DAQ) board optimized for superior accuracy at fast sampling rates. For increased measurement accuracy, consider the high-accuracy M Series devices with a 18-bit analog-to-digital converter providing a 4X resolution increase.

High-speed M Series devices incorporate advanced features such as the NI-STC 2 system controller, NI-PGIA 2 programmable amplifier, and NI-MCal calibration technology to increase performance and accuracy. High-speed M Series devices have an onboard NI-PGIA 2 amplifier designed for fast settling time at high scanning rates, ensuring 16-bit accuracy even when measuring all channels at maximum speeds. To learn more about M Series technologies, device specifications, and information on recommended cables and accessories, please refer to the data sheet and specifications.

Driver Software

M Series devices work with multiple operating systems using three driver software options including NI-DAQmx, NI-DAQmx Base, and the Measurement Hardware DDK. Browse the information in the Resources tab to learn more about driver software or download a driver. M Series devices are not compatible with the Traditional NI-DAQ (Legacy) driver.

Application Development Environments

With NI LabVIEW, you can create custom data acquisition applications with the ease of graphical programming and power of more than 500 analysis functions and advanced programming tools. LabVIEW Full and Professional Development Systems include LabVIEW SignalExpress for interactive data logging. M Series data acquisition devices are compatible with the following versions (or later) of NI application software – LabVIEW 7.x, LabWindows™/CVI 7.x, or Measurement Studio 7.x; LabVIEW SignalExpress 1.x; or LabVIEW with the LabVIEW Real-Time Module 7.1. M Series data acquisition devices are also compatible with Visual Studio .NET, C/C++, and Visual Basic 6.
APPENDIX G

SpikeSafe Tj Measurement System

Thermal Resistance, Tj, K-factor Measurements

- Supports 1 or multiple DUTs
- Production in-situ Vf, RΘ, and solutions available
- Industry Standard JESD51-1 Electrical Test Method
- Supports Static or Dynamic Methods
- Data Logging to .csv file

One device Thermal Resistance System components include SpikeSafe current source, low current module, high speed sampling voltmeter, cabling and software application.

Overview
The Thermal Resistance System provides an easy and accurate solution for determining K-Factor and measuring diode thermal resistance (RΘ) and junction temperature (Tj) using the industry standard JESD51-1 Electrical Test Method. System configurations are available to support automated test of 1 device, 80 devices or more. Using the SpikeSafe 200 and the Tj Measurement System, Tj and RΘ can easily be measured under high common mode voltage conditions, such as those found in series lighting circuits.

Tj Utility Application
The Tj Utility Application automates various Tj measurement steps. It features easy to use wizards that support automatic K-factor calibration and reference temperature measurement. The Tj Utility can take single Tj and RΘ measurements, or it can be set to continuously monitor these parameters. Voltage measurement samples and the calculated Tj and RΘ values are continuously logged to a file. The Tj Utility works with external in-place thermal management systems, such as ovens or thermal control platforms.

Low Current Module
The Low Current module provides an adjustable DC current level from 0-6mA (0-24mA with high bias option). This module is factory installed in the 2U SpikeSafe 200 Chassis. A lockable potentiometer on the rear panel is provided for adjustment. This source is integrated into the SpikeSafe 200 and controlled with the SpikeSafe 200 Control Panel Application.

Applications
- LED Testing
- Lighting fixture design
- Thermal Modeling

Windows based Tj Utility Application

www.vekrex.com
SpikeSafe 200 Tj Measurement System

Industry Standard Electrical Test Method
The industry standard JESD1-1 Electrical Test Method measures Tj using the diode junction's inherent voltage/temperature dependency. The diode is driven with a two-level pulsed current and voltage measurements are taken at both levels. These measurements are used to calculate Tj and R0.

K-Factor Calibration
A diode's voltage/temperature dependency is first characterized by a technique called K-factor calibration which uses a small measurement current level to bias the junction above the cut-in voltage. Vektrex's K-factor wizard is an easy to use application that simplifies retrieving these necessary measurements.

Specifications

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<tr>
<td>Measurements:</td>
<td>Vt heating, Vt measurement, Tj, R0</td>
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<tr>
<td>Tj Resolution:</td>
<td>0.1 degrees C</td>
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<tr>
<td>Tj Accuracy:</td>
<td>Dependant upon K-Factor calibration +/- 0.25°C typical</td>
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<td>Data Logging:</td>
<td>1 set of log entries/SpikeSafe pulse</td>
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<td>Measurement Position:</td>
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<td>Measurement Period:</td>
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</tr>
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</table>

Applications

Tj Utility, K-Factor Wizard: Windows XP

For more information see www.vektrex.com
Contact: Malisa Ford
Phone: (516) 519-2332 x6
malisa@vektrex.com