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A Technique for the Direct Measurement of the Junction Temperature in Power Light Emitting Diodes

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***Abstract*—Measuring the actual junction temperature T_J of power light emitting diodes used in high-end luminaires is important for implementing measures to reduce the stress and therefore extend the lifetime of these fundamental light sources. The direct measurement of this key parameter can be performed by imposing a known and precise forward current I_{probe} through the LED, and tracking the bias voltage appearing at its terminals. The technique proposed in this paper is based on the same approach, but does not require a stable current source, relying instead on the exponential fitting of random *I-V* measurements and on the estimation of the bias voltage at the proper I_{probe} through a mathematical interpolation. The technique is implemented on a custom-designed circuit, and experimental data are obtained on commercial power LEDs, allowing to assess the impact of I_{probe} and sampling current range on the measurement error.**

***Index Terms*— Temperature sensors, Temperature control, Light emitting diodes, Junction temperature**

I. Introduction

LIGHT emitting diodes (LEDs) are by far the most efficient light source in modern luminaires, converting more than 90% of the electric energy into visible photons. Additionally, they are renowned for their long lifetime, as they largely overcome incandescent, fluorescent and arc bulbs in terms of lifetime, often remaining operative for several tens of thousands of hours. Thanks to these attractive characteristics, LEDs luminaires are rapidly replacing old ones at global level, both in indoor environments and in streetlighting. This technology, however, has a potential drawback that is often underestimated by end users, as LEDs suffer relatively small temperature variations much more than other light emitting technologies. As an example, while an incandescent bulb can safely operate at temperatures as high as several hundred degrees Celsius, operating an LED at around 100 °C can dramatically cut its expected lifetime, beside degrading its efficiency and emitted light spectrum [1]-[5].

In order to keep this problem under control, a constant tracking of the device temperature is essential. However, as for any other solid-state device, LED manufacturers are used to refer technical specifications to the absolute maximum junction temperature, T_J, where the junction is in fact a very limited portion of the internal volume of the semiconductor dice, and is therefore inaccessible in practice. It turns out that luminaire designers are called to infer the actual T_J by combining other parameters and measurements, like the die-to-case thermal resistance, the dissipated electric power, the ambient (or heat sink) temperature [6]-[7], which obviously only provide approximate values, moreover with a slow dynamic. Although several physics-based techniques exist to get more precise measurements of T_J, their implementation is unpractical in luminaires [8]-[12].

Recently, the well-known dependence of the voltage V_{pn} appearing across a p-n junction, biased at a fixed current, and its T_J, has been thoroughly characterized in off-the-shelf power LEDs, showing that this dependence is almost perfectly linear when the probe current is chosen within a proper range, and the measurement error is of the order of a few °C for temperatures up to 130 °C [13]. Both these results pave the way to an easy tracking of an LED T_J with low cost circuits. Moving from these results, in this paper we show that said technique does not necessarily require that the V_{pn} is measured at a fixed current, because a burst of random acquisitions (I, V_{pn}) is in fact sufficient to calculate the actual T_J. This technique thus allows for an easier and a more flexible implementation of the T_J measurement and control strategies in power LEDs.

The paper is organized as follows: Section II summarizes the theory behind the measurement technique and the results obtained to date. Section III describes the modified technique, not requiring the generation of a fixed probe current; in Section IV and V we present, respectively, the relevant circuit and the experimental results obtained on commercial power LEDs.

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Conclusions are drawn is Section VI.

II. Theory

LEDs are solid-state light sources that rely on the physics of forward biased p-n junction diodes to convert current into photon emission through the radiative recombination of electron-hole pairs [14]. As with any other diode, at a first approximation the total current I flowing through an LED can be modeled by the classical exponential equation:

$$I = I_0\left(e^{\frac{V_{pn}}{nV_T}} - 1\right), \tag{1}$$

where n is the ideality factor, I_o is the saturation current, V_T is the thermal voltage kT/q, with k the Boltzmann constant, T the absolute temperature and q the electron charge. By neglecting the unity in (1), V_{pn} can be calculated as:

$$V_{pn} = n\frac{kT}{q}(lnI - lnI_0), \tag{2}$$

where I_o is itself a temperature-dependent parameter according to (3) [15],[16]:

$$I_0 = C\,T^{\alpha}\,e^{-\frac{E_g}{kT}}. \tag{3}$$

Here E_g is the extrapolated energy gap of the semiconductor at 0 K, while C is material and junction area dependent, and α is a constant (*e.g.* $E_g = 2.25$ eV, $C = 9.8\times10^{-8}$ A, $\alpha = 2.5$ for a GaP LED [16]). By using (3) in (2), one obtains the following expression for V_{pn}:

$$V_{pn} = n\frac{kT}{q}[lnI - lnC - \alpha\,lnT] + \frac{n}{q}E_g. \tag{4}$$

This equation predicts an almost linear dependence of V_{pn} on T, as the lnT term changes by only 4.2% in the temperature range from R.T. to 380 K, which can be considered the practical safe operating range for power LEDs.

Measurements have in fact demonstrated a very strong linear dependence between V_{pn} and T on several junction devices, with experimental data showing a coefficient of determination R^2 [17] in excess of 0.9999, provided the forward probe current is chosen within a proper range, which depends on the specific device [18]-[22]. In this case, (4) is well approximated by a relationship of the type:

$$V_{pn} = S \cdot T + Q, \tag{5}$$

with S and Q, respectively the slope and the constant term of the linear regression of the experimental points.

S and Q values characterizing two commercial power LED models were extracted in [13], in a wide probe current range. There, at 1000 different probe currents, these two parameters were extracted from the best linear fit of a wide set of experimental (V_{pn}, T) couples measured at each temperature on several devices bearing the same part number. Standard deviations of S and Q, and root mean square errors, were also calculated at each probe current. A PT100 sensor with an accuracy of 0.2 °C was used as the reference sensor.

Once these two coefficients are known, equation (5) allows to track the T_J of a power LED by simply imposing, at some time, a known current and measuring the voltage appearing at its terminals [23]-[26].

However, imposing a precise bias current by means of a linear circuit, such as a bandgap reference, might limit its flexibility for several reasons. For example, the best probe current for a specific LED may change with aging, or in general it differs among LEDs with different part numbers. Therefore, to allow for an easy customization of the I_{probe}, or even consider a multi-current probing approach on the same device, we use hereafter an alternative method which, based on a microcontroller unit, drops the stringent necessity of a stable and precise current source, yet providing high precision.

The device type considered in this work is an off-the-shelf white light power LED [27], with typical *I-V* characteristics shown in Fig. 1 at several practical operating temperatures, measured after 1800 h of operation at 500 mA at an average junction temperature of 80 °C. We will assume hereafter the average S and Q values determined therein on a batch of devices, to calculate T_J in the temperature range from 25 °C to 135 °C.

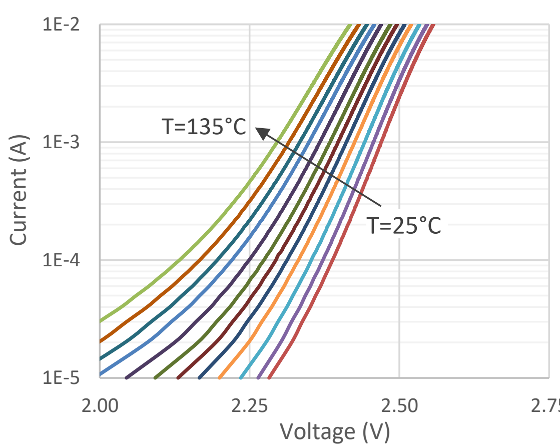

Fig. 1. Current-voltage characteristics of one LED [27] at different temperatures, after 1800 h stress at 500 mA forward bias at 80°C.

III. The T_J Measurement Procedure

The method used here to perform T_J measurements on power LEDs consists in biasing the LED with a bunch of random voltages laying in a range that in turn produces currents that are comparatively close to the optimal I_{probe}, and afterward calculating by interpolation the V_{pn} to be used in (5). A microcontroller-based circuit has been designed to implement this procedure and experiments have been performed to assess its precision. In essence, a sequence of random, yet gradually rising, bias currents is flown through the LED. At each sampling, the current-voltage couple is memorized only if the measured I_F is within a pre-determined range of values I_{Fmin}, I_{Fmax} including I_{probe}, until K pairs are acquired. Afterwards, an interpolated function $I_F(V_F)$ is determined from the K couples and the voltage V_{pn} at the optimal I_{probe} is inferred from it. Finally, the calculation of the junction temperature is made through (5).

In principle, the interpolated function $I_F(V_F)$ can be obtained *e.g.* by linear, polynomial or exponential regression. Given the

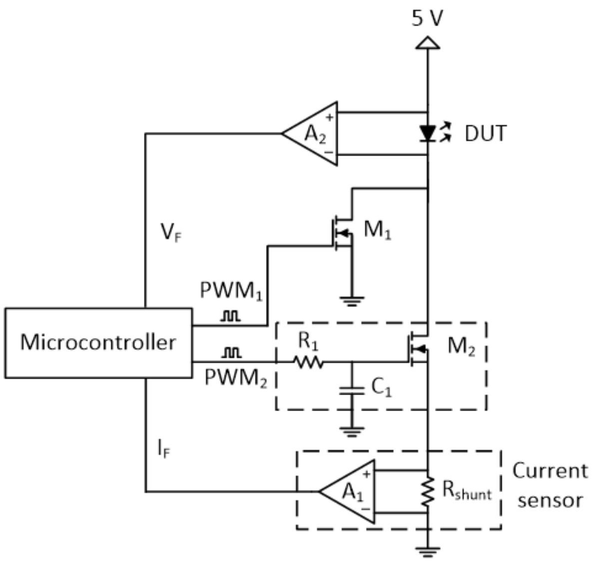

Fig. 2. Schematic of the LED junction temperature measurement circuit.

exponential nature of (1), in our technique we opted for the best linear fit of the log*(I)*-*V* couples associated to the *K* acquired samples. A linear regression algorithm based on the method of least squares was adopted to fit, at each run, the experimental data.

In order to assess the impact on the final results of the method key parameters, such as the I_{Fmin}, I_{Fmax} range width, the I_{probe}, the number of couples *K*, several tests were performed and the corresponding measurement errors compared.

IV. Circuit Description

The junction temperature measurement technique can be implemented through a microcontroller unit with basic features, provided *i.e.* with a pulse-width modulation (PWM) module and a 12-bit analog-digital converter (ADC) at least. As a proof-of-concept, the circuit was built around a NUCLEO-F401RE board equipped with an STM32 microcontroller (ARM® Cortex®-M4) [28], mounting a custom designed printed circuit board (PCB) including the analog front-end circuitry and the LED connectors. The measurement circuit schematic is shown in Fig. 2, while actual board is shown in Fig. 3. During the normal operation of the LED, an NMOS transistor (M_1) connects the device cathode to ground, controlled by a PWM (PWM_1) generated by the microcontroller. While operated in this mode, the duty cycle sets the desired average LED current (*e.g.* 500 mA). The PWM_1 frequency is higher than 1 kHz to avoid LED flickering.

At the start of the T_J measurement routine, M_1 is turned off and a second NMOS (M_2) connects the LED cathode to ground via a shunt resistor. PWM_2, applied to a low pass filter (R_1 = 4.7 kΩ, C_1 = 6 µF), has a gradually increasing duty-cycle, producing a voltage ramp at the gate of M_2, which in turn allows the LED to

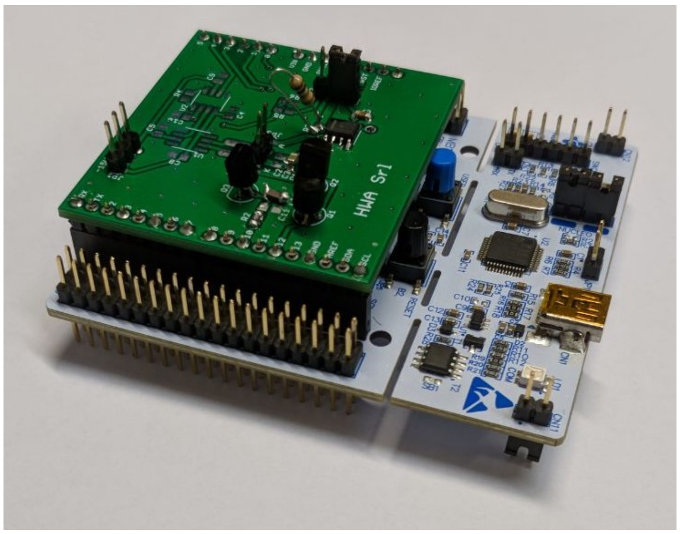

Fig. 3. Picture of the microcontroller-based acquisition circuit.

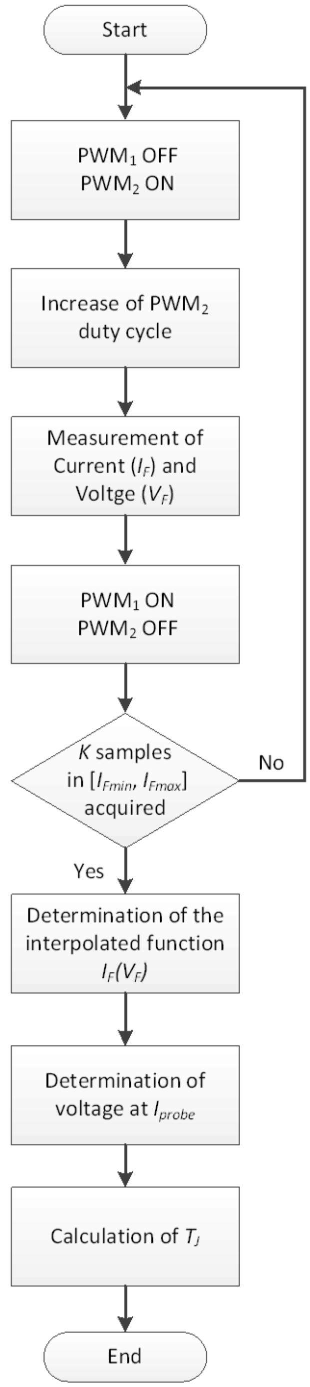

Fig. 4. Flowchart of the method for measuring the LED junction temperature.

be flown by rising currents laying in the desired probe range I_{Fmin}, I_{Fmax}. During this ramp, K samples are acquired, but the LED is turned-on by M_I between two samplings, in order to avoid flickering. The current is measured over the shunt resistor (R_{shunt} = 1 Ω) through a current sense amplifier (INA285) with a gain of 1000 V/V, while the LED voltage is measured through an instrumentation amplifier (LT1167) with a gain (4.3 V/V). The two voltages are acquired on two separate channels of the ADC. The whole ramp, and then the measurement routine, takes less than 300 ms. At the end of the measurement routine, the LED is definitively turned back on by M_I. In real world applications, the full circuitry can be simplified and integrated in a single LED driving chip.

A custom-built linear regression routine [29] is afterwards run by the microcontroller, and applied to the K pairs log*(I)*-*V*, and the V_{pn} voltage corresponding to the previously defined I_{probe} current is calculated through interpolation. Finally, the junction temperature T_J is calculated from (3), using therein the proper sensitivity S and intercept Q values stored in the microcontroller, unique for all the devices with the same part number.

The whole procedure is also described in the flow-chart of Fig. 4.

We can expect that the LEDs in a string operate with different junction temperatures, depending on the fabrication tolerances, at die level as well as at thermal dissipation level, the latter in turn susceptible *e.g.* to the soldering process quality. In relation to this, it should be noted that there are no impediments in extending the technique to as many LEDs in the string as necessary. The measured current would be the same, while each voltage drop could be measured through a single differential amplifier, cyclically switched among all LEDs by means of analog switches. This would be an advancement compared to the standard approach of temperature monitors relaying on external sensors, which necessarily provide approximate temperature values.

V. Experimental Results

The T_J measurement method and circuit described in Section III and IV were assessed in accuracy by performing tests on several LEDs [27]. The devices were soldered on a single alumina PCB with metal backplane. The study was carried out by heating the devices in a high-precision temperature-ramped oven [30]. To prevent self-heating, the characterization tests were performed by setting PWM_I to zero all the time. Measurements were made in the temperature range from 25 °C up to 135 °C. Each measurement routine was launched only after having verified that the temperature inside the oven had stabilized for a few minutes.

The actual LED temperature T_{actual} was monitored through a thermocouple having an accuracy of 1.1 °C, placed in tight contact with the alumina board, very close to the devices.

Examples of the agreement between the calculated and the actual temperatures for three sample devices are shown in Fig. 5. All of the shown points were obtained by acquiring, at each temperature, K = 10 random current-voltage samples laying in the current range from 1 mA to 10 mA, interpolated to calculate V_{pn} at the best probe current I_{probe} = 8 mA. The calculated V_{pn} is then used in (5) to extract T_J. The S and Q

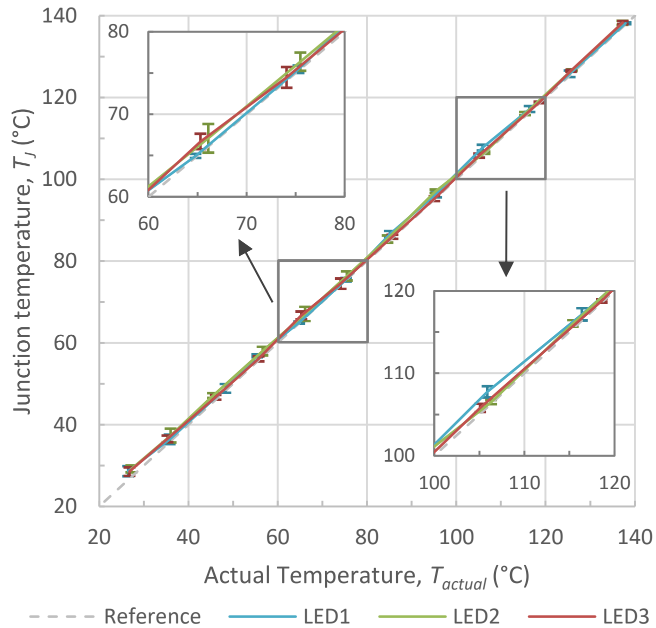

Fig. 5. Extracted T_J vs. the actual LED temperature T_{actual} for three samples with the same part number [27]. At each temperature, extractions were made by acquiring 5 random current-voltage samples in the current range 1 mA to 10 mA, afterwards interpolated to obtain V_{pn} at the best probe current I_{probe} of 8 mA. The vertical bars, shown at each test temperature, separately for each sample, represent the 3σ interval calculated over 5 subsequent extraction routines. The grey broken line is the ideal $T_J = T_{actual}$ line, while the continuous lines are a guide-to-the-eye for the three LED responses.

coefficients are in this case -1.288 mV/°C and 2.583 °C, respectively. The vertical bars in Fig. 5 show, at each test temperature, the 3σ interval calculated over 5 subsequent extraction routines for each device. The absolute maximum error over all extractions is 2.57 °C (LED1 at T_{actual} = 25 °C), while the mean error is 0.91 °C (all LEDs).

Table I summarizes the results of several other tests, in which the sampling current range (I_{Fmin}, I_{Fmax}) and the probe current I_{probe} were changed. Also, K = 10 for all tests, and the extraction routine was repeated 5 times to check the repeatability. A color scale from green to red is used for first-glance comparison purposes among cells of the same column, with the green and red cells respectively highlighting the best and worst results. The best performances are observed for the second row combination (I_{Fmin} = 1 mA, I_{Fmax} = 10 mA, I_{probe} = 8 mA). By comparing cells with the same I_{probe}, it turns out that the wider the I_{Fmin}, I_{Fmax} range, the higher the error. In fact, when the interpolation is performed on a reduced current range, a better fitting of experimental *I, V* data to a simple exponential function of the type $I = A \times exp(B \times V)$ can be expected. This is clearly seen in Fig. 1, showing that the LED characteristics change their slopes, and therefore the ideality factor n, as the different current regimes are crossed, especially at high temperatures. Besides, it is evident that the low current regimes (I_{probe} < 0.1 mA) are more affected by n variations, which makes exponential interpolation less precise. However, reducing the sampling current range implies a more careful implementation of the PWM_2 duty-cycle ramp.

Finally, the left-most column reports the maximum peak-to-peak error, namely the sum between the highest

TABLE I
EXTRACTED T_J ERRORS UNDER DIFFERENT SAMPLING CONDITIONS

Current range I_{Fmin}, I_{Fmax} (mA)	Probe current I_{probe} (mA)	Mean error (°C)	Maximum standard dev. (°C)	Maximum error (°C)	Temperature of maximum error (°C)	Peak-to-peak error (°C)
1, 10	10	1.43	1.17	4.45	26.8	4.85
1, 10	8	0.91	0.73	2.57	26.5	3.85
1, 10	5	1.11	1.06	3.20	26.5	4.03
1, 10	2	1.25	1.59	4.57	137.3	6.14
1, 10	1	1.94	1.75	6.21	45.5	8.31
0.1, 10	10	1.59	1.80	7.21	137.3	11.82
0.1, 10	8	1.02	1.02	3.36	27.2	5.36
0.1, 10	5	1.15	1.02	3.25	26.5	4.80
0.1, 10	2	1.42	3.34	12.31	137.3	14.14
0.1, 10	1	2.06	3.98	13.19	137.3	13.91
0.1, 10	0.5	2.26	2.26	8.74	125.9	12.78
0.1, 1	1	1.73	2.13	7.06	118.6	11.47
0.1, 1	0.5	2.17	4.12	11.86	137.3	12.77
0.1, 1	0.2	3.60	6.79	18.53	137.3	21.30
0.1, 1	0.1	5.34	4.54	14.46	116.4	19.86

Comparison of the quality of results from temperature extraction procedures performed in different conditions. The mean error and the maximum standard deviation are cumulatively calculated over three devices and over five subsequent extractions; the maximum error and the peak-to-peak error are referred to the worst device and worst extraction run. The cells are colored according to a color gradient, with green and red representing the best and worst results respectively.

in-excess and in-defect errors all along the T_J vs. T_{actual} graph.

The accuracy of the analog front-end circuit and of the reference sensor, and the initial LED calibration, contribute to the reported errors. Among them, the statistical variability in the LEDs characteristics has a notable impact through S and Q tolerances, as reported in [13].

Extractions were also performed by interpolating over more V, I pairs, up to $K = 25$, not reported in Table I, but this did not significantly affect the measurement accuracy.

A comparison among the performances of several T_J measurement tests found in literature using the V vs. T_J relationship is provided in Table II. The results obtained with the proposed technique are comparable to those observed on other devices, although only few sources include error estimation data.

VI. CONCLUSION

Power LEDs operating temperature is commonly measured by commercial LED drivers in order to limit the current in case of overheat, a strategy that eventually allows to lower the costs of dissipation systems. External sensors, placed on the LEDs' board, are used to perform this task.

TABLE II
COMPARISON AMONG POWER LED T_J ESTIMATION TESTS BASED ON CURRENT-VOLTAGE MEASUREMENTS

LED type	Probe current (mA)	Temperature coefficient, S (mV/°C)	Smallest error (°C)	Ref.
GaP	0.1	-2.34	-	[16]
1 W, white	0.1	-1.648	-	[24]
1 W, white	2	-	0.99	[25]
GaN UV	10	-2.3	-	[26]
Blue, 1 mm^2	10	-1.043	1	[31]
6×LED, white luminaire	5 to 270	-7.58 to -14.97	-	[32]
1.2 W	10 to 25	-	0.58	[33]
3 W, white	0.6	-1.835	0.75	[13]
6 W, white	8	-1.288	0.91	this work

The measure of the more useful internal temperature of the device, actually the junction temperature T_J, can be however performed by exploiting the linear dependence between T_J and the forward voltage V_{pn} appearing between the device terminals, but it requires a very stable current source.

A modified procedure for measuring T_J of power LEDs was proposed and duly characterized in this work. It requires forward biasing of the LED with a sequence of a random currents while measuring the voltage drops at its terminals. A best exponential fit is performed afterwards to infer the voltage drop V_{pn} at a pre-determined optimal probe current I_{probe}, from which T_J can be calculated, provided the linear relationship $V_{pn} = S \times T_J + Q$ for the specific LED type is known from previous characterizations.

The technique was implemented by making use of a microcontroller with standard performances, and a bunch of small-sized and low-cost additional components. The custom circuit controls the LED current both during the on-phase and the measuring routine.

Several experimental tests were iterated on samples of commercial high-power LEDs. Each measurement routine consists of several current-voltage samplings, 10 in our tests, each taking less than 1 ms, interleaved with periods of full current (LED on) to avoid flickering.

The new implementation presents advantages in terms of flexibility, as the measurement parameters can be easily modified through the microcontroller firmware. Measurements demonstrate that, in the temperature range of 25 °C to 135 °C, the peak-to-peak error can be contained below 4 °C. Measurements have also shown that the exponential interpolation does not work equally well in all current ranges, due to the regime-dependent ideality factor of the junction.

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