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Thermal Inductance in GaN Devices

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***Abstract*— Using the analogue of the electric inductance, we reveal the properties of the thermal inductance in GaN-based light-emitting diode (LED) devices by testing their transient thermal behaviours. We find that the devices exhibit a transient thermal response under step-down or step-up currents and observe notable inductive phenomena of the temperature response as time evolves from start up to some hundred microseconds. We define thermal inductance as the rapid change in device temperature that is opposite to the temperature change expected from the power input. These findings can promote new temperature measurements, and novel thermal analyses of high-frequency semiconductor devices that combining the thermal resistances, thermal capacitances, and thermal inductances.**

***Index Terms*— Thermal inductance; transient thermal behaviour; thermal analysis.**

I. INTRODUCTION

The heat flow in conductors can be modelled using equivalent circuits, in analogue to the flow of electric charge. The thermal resistance (R) and thermal capacitance (C) are then used to construct a compact model that can accurately predict *i.e.* the dynamic junction temperature response[1]. Only RC-networks have been widely applied for thermal conductors so far. Very few studies on inductive phenomena or thermal inductances (L) have been reported. In 1946, Bosworth [2] demonstrated that the heat flow also can have an inductive character according to the experiments in a fluidic system. He claimed that the measured transient behaviour of the temperature could not be explained by a mere combination of thermal resistance and thermal capacitance. Bosworth later extended his experiments to study the thermal mutual inductance[3]; however, the studies on thermal inductance were limited to fluid flows. In the present study, we investigate the transient thermal properties of GaN-based solid-state light-emitting diode (LED) devices. We argue that the transient thermal behaviour can be described by a function that is analogous to the electrical inductance.

To thermally evaluate the cooling performance and even efficiencies, reliabilities, etc., the junction temperature (Tj), which is referred to as the highest operating temperature of the actual semiconductor in an electronic device, is the most critical and precise parameter[4, 5]. As the GaN chip is hard to examine directly due to its encapsulation, indirect methods are more preferred. Xi et al. were able to measure Tj in deep ultraviolet LEDs with three different methods [4, 6]. They proved that the diode-forward voltage (V_f) method is the most accurate one. In this method, the Tj of the solid-state LED device is determined with electrical testing methods. A pulsed or step-down current is applied in the Tj determination in order to find the forward voltage–temperature (V_f–T) characteristics of the p–n junction[4, 6, 7]. However, most researchers have neglected the very start of the transient response of the electric parameter in the measurement, leading also often to unacceptable measurement errors. In 2013, Ye et al.[8] were the first to experimentally reveal the inductive response from a change in applied power, and they conducted also experiments to improve the accuracy of the Tj measurement. In this work, we show that a thermal inductance can be regarded a general property of GaN-based LED devices.

II. EXPERIMENTS AND RESULTS

A GaN-based high-voltage LED chip was attached on a silicon submount through a thin thermal interface layer (TIM). Temperature sensors were fabricated, using standard silicon processing technologies, and calibrated for use in the range 30-150 °C. The thicknesses of the chip and the TIM were 153 and 59 μm, respectively. The sensors were positioned adjacent to the p-n junction in order to monitor the dynamic temperature behaviour and the approximate value of the Tj was found by them (see in **Fig. 1**). The set-up was first stabilized at low current (100 μA), until the junction and temperature sensors were equilibrated with the thermal plate. A step-up current was next applied to the LED chip, and the behaviour of the voltage of the GaN chip was precisely recorded. The voltage increased sharply from 56.462 V to 66.554 V within 0.1 ms after the current change. Then, the voltage dropped gradually to 64.842 V. Secondly, the LED chip was powered with a current of 15 mA until stable conditions were observed. A step-down current of 100 μA was then applied. As a consequence, the voltage decreased from 64.842 V to 55.362 V during 0.1 ms. Then the voltage gradually rose until 56.462 V. The Tj was calculated

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from the measured V_f using the method as described in reference [8]. Meanwhile, the temperature sensors were continually recording all temperature changes under the step-up and set-down currents.

In this work, we define 'recovery time' as the interval from the start of a power change to the time at which the temperature again becomes equal to the initial temperature value. The results show that the Tj decreases significantly and immediately when a high current is applied (**Fig. 2 A**). Then, the Tj gradually increases. After a recovery time of ~100 ms, the Tj reaches the initial value. The temperature of the LED chip continues to increase until the system reaches a steady state at Tj of 61.4 ºC, with a sensor temperature of 59.2 ºC. At the steady state of 15mA, the applied high current is instantly reduced through a step-down mode (**Fig. 2 B**). The measured Tj increases by 4 ºC within 0.1 ms. The sensor temperature simultaneously shows a temperature increase of 2 ºC. Subsequently, the Tj gradually decreases. After a recovery time of ~100 ms, the Tj and sensor temperature decrease to their initial values. The Tj continues to decrease until the system achieves steady state at room temperature. Notably, the response in Tj is in opposition to the power change in the chips. The total power applied to the LED is partially converted to thermal dissipation (thermal power) and partially converted to light. We therefore describe the thermal power of the devices excluding the optical energy in **Fig.1**. The thermal power ratio @15mA/@100μA during the step-up current and 1/(@100μA/@15mA) during the step-down current are presented. The thermal power measurements were constant in the beginning for conditions at 100 µA in the step-up current and 15 mA in the step-down current. In the trainset periods, the thermal power ratios changed from 141.71 to 138.07 (@15mA/@100µA) and from 140.81 to 138.07 (1/(@100µA/@15mA)), respectively. The large thermal power ratios were the reasons leading in both cases to opposite Tj change. These observations fit with the explanation of a thermal inductance, firstly introduced by Bosworth.

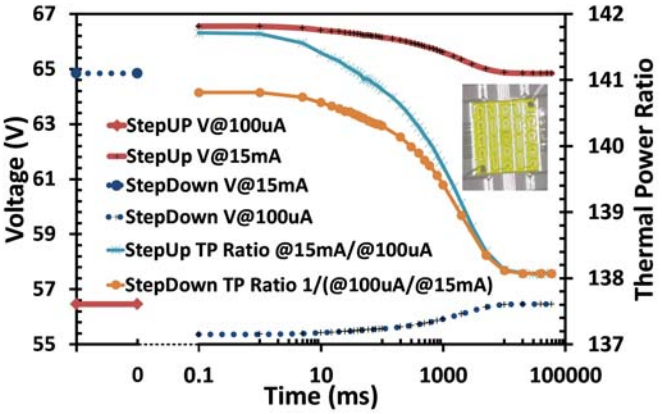

Fig. 1 | The forward voltage change with a step-up current from 100µA to 15mA and a step-down current from15mA to 100µA; the thermal power (TP) ratio @15mA/@100µA and 1/(@100µA/@15mA) during the step-up and the step-down current.

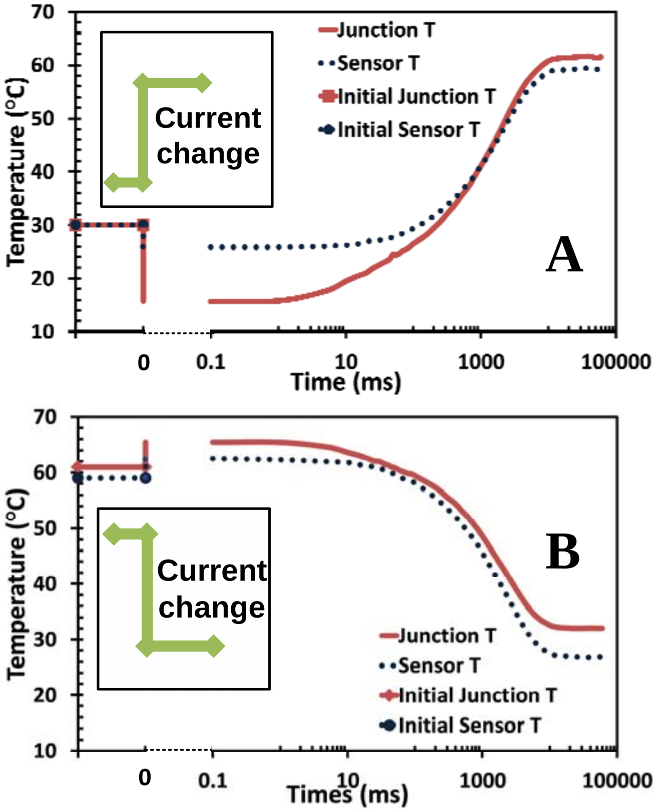

Fig. 2| Thermal inductive response as the transient current applied on a GaN-based high-voltage LED chip. (**A**) Junction temperature measured by the forward-voltage measurement and sensors with a step-up current from 100µA to 15mA. (**B**) Junction temperature measured by the forward-voltage measurement and sensors with current drop from15 mA to 100µA.

The transient characteristics of Tj as a function of applied current were further investigated. Instead of a high-voltage LED chip, a GaN-based low-voltage LED chip was examined.

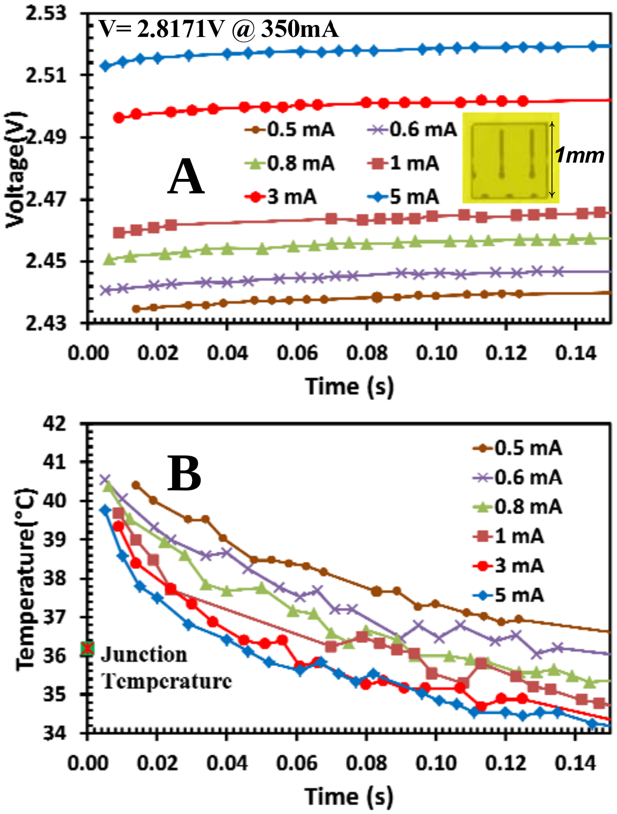

Fig. 3| Thermal inductive response as the transient current applied on a GaN-based low-voltage LED chip. (A) Measured forward voltage with the formed step-down currents from 350mA to 5, 3, 1, 0.8, 0.6, 0.5 mA. (B) Junction temperature change measured by the forward-voltage method due to the step-down currents.

This chip can withstand a wider range of applied currents and allows more precise power changes and therefore better observation of thermal inductive responses. The chip was mounted on a lead frame and encapsulated with silicone. The chip package was soldered to a metal core printed circuit board and mounted on a thermal plate with controllable temperatures. The Tj of the LED chip was measured as a function of time while the applied current was stepped.

Fig. 3 (A) shows the measured forward voltages of six groups with applied step-down current, from 350 mA to a lower current value. **Fig. 3 (B)** shows the measured transient Tj's according to the respective forward voltages. We calculated Tj is equal to 36.2 ºC at 350 mA. These observations are consistent with the thermal inductive measurement in the GaN-based high-voltage LED chip. The Tj suddenly rose and gradually decreased as the current was stepped down with a proportional temperature change for various power ratios. The recovery time was slower for the system with a larger step level decrease.

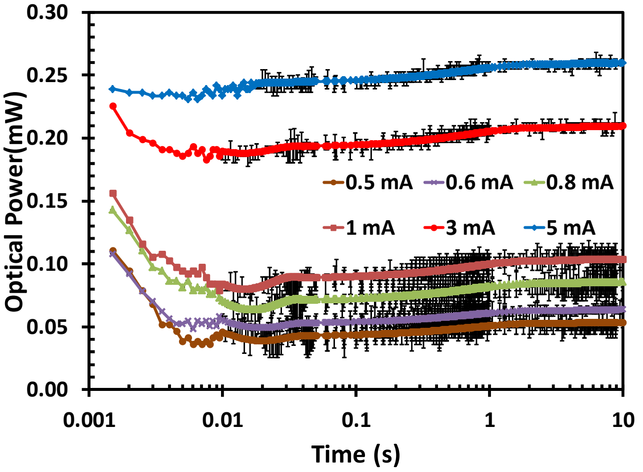

Fig. 4 | Optical power change as the transient current applied on a GaN-based low-voltage LED chip measured by a fast-response optical sensor under the formed step-down currents from 350 mA to 5, 3, 1, 0.8, 0.6, 0.5 mA.

It is expected when a current is applied to a solid-state LED device, that heat is immediately generated, leading to an increase in Tj. Conversely, it is expected that the temperature will decrease when the power decreases. However, the present experiments reveal an different situation that a phenomenon that has remained unobserved so far. In a given moment, the Tj changes in a manner opposite to the earlier expected response, when a transient current or a transient power is applied to the device. This transient thermal process cannot be modelled by an equivalent circuit which involves a combination of only thermal resistances (R) and thermal capacitances (C). But the transient phenomenon can be described by adding thermal inductances (L), with the functional form of:

$$\Delta T(t) = -L\frac{dQ}{dt} \tag{1}$$

Where L is the thermal inductance, dQ/dt and ΔT are the change in power and temperature, respectively, and t is the time. This equation can explain on an overall level how a change in power in a device incudes a proportional, but opposite temperature change rather than the temperature change expected from the power input.

The total energy in a LED is partially changed into heat and partially into light. One reason for the sudden change in temperature may be possibly related to the creation of photons. Then we also investigated on the transient optical emission. The optical power changes of the GaN-based low-voltage LED chip were measured by a fast-response optical sensor, for the six groups of step-down currents experiments in **Fig. 3** and recorded in **Fig. 4**. The optical power in the 1W LED chip dropped at first and became constant at 0.25, 0.21, 0.10, 0.08, 0.06, or 0.05 mW after 1000 ms. It was therefore concluded that transient optical effect occurs in the chip; but that the optical power change accounts for only a small percent of the total power input. The major energy change to thermal dissipation is always dominated. So, the transient optical power cannot affect or explain a temperature increase for reduced power input.

A thermal inductive property of a solid state system has not been reported previously; nevertheless, a similar phenomenon has been observed in thermoelectric devices. The detailed structure of the LED chip is considerably different from that of a typical thermoelectric device. But bulk GaN has been reported to show a notable thermoelectric effect[9, 10]. Empirical equations for thermal inductance can be derived from knowledge of transient thermoelectric effects in semiconductor devices. The physical behaviour of the step-up or step-down current in the p–n junction was described by differential equations in one dimension in [11, 12]. A linear approximation resulted in a predicted super cooling [11, 12] of thermoelectric devices under current change, following:

$$\Delta T_L = \Delta T_\infty \left(\frac{P-1}{P+1}\right) \tag{2}$$

where ΔT_L is the maximum temperature difference when a step-down/up current is used, and P ($P = I/I_M$) is the ratio of the current change from the operating current (I) to the lower current (measuring current I_M) or inverse change from the lower current to the high current. In addition, ΔT_∞ denotes the temperature difference, assuming that the step-down/up current ratio occurs is infinitely large ($P = \infty$). The time when the current suddenly changes was defined as zero time, and t_L is the recovery time from zero time to when the temperature at low measuring current is equal to the temperature at the operating current. The Tj measurement can be corrected, once the recovery time t_L is known. Thus, the empirical equation (3) can be applied to calculate t_L from experiments, with the time constant τ and material and structure factor ϵ:

$$t_L = \tau(P-1)^{\epsilon} \tag{3}$$

III. CONCLUSION

We have proven that a rapidly changing power in GaN-based LEDs induces a proportional temperature change, which is opposed to the temperature change expected from the power input. The phenomenon was referred to as a thermal inductance in this report. The origin of the thermal inductive properties may be thermoelectric effects. We considered the thermal inductance that occurs in GaN devices with a p–n junction. With the combination of the thermal resistance, the thermal capacitance, and the thermal inductance, we expect to be able to give the more precise thermal analyses of high-frequency GaN devices. We also expect that thermal inductance phenomena exist more widely than noted so far, in nonhomogeneous materials. This may have a bearing on the field of thermal analyses under energy changes on very short time scales.

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