Utilizing Electroluminescence of Silicon IGBTs for Junction Temperature Sensing

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***Abstract*—Online condition monitoring of power electronic systems relies on high-bandwidth junction temperature information. However, existing temperature sensing methods for IGBTs, such as temperature-sensitive electrical parameters (TSEPs), are often susceptible to electromagnetic interference and difficult to extract in high-voltage applications. To overcome these limitations, this work presents a sensing method that extracts junction temperature information by measuring a temperature-sensitive optical parameter (TSOP), the electroluminescence (EL) of Si IGBTs. The sensing approach extracts the EL with optical fibers and, thus, provides intrinsic galvanic isolation. The proposed sensing approach is characterized and experimentally validated by dynamic measurements on a commercially available IGBT power module.**

***Index Terms*—IGBT, electroluminescence, temperature-sensitive optical parameter (TSOP), condition monitoring**

I. Introduction

Power electronic systems play an increasingly important role in safety-critical applications, such as autonomous vehicles [1], [2], electrical aircrafts [3] or offshore wind farms [4], which require high reliability of the semiconductors. To meet the reliability requirements of these systems, junction temperature sensing is a key technology as it enables to monitor the state-of-health of the semiconductor components and thereby allows detecting critical degradation [5]–[7]. Moreover, online junction temperature sensing allows active thermal control [8]–[13] and management [10], [14] to reduce thermal stress in power modules and increase peak-current capability, respectively. To measure the junction temperature of power semiconductors during operation, various sensing techniques have been researched in recent decades, with TSEPs regarded as the most promising solution, such as the forward voltage [15], [16], gate charge time [17], turn-on delay [18] and gate plateau level [19]–[21]. A significant challenge in measuring these electrical parameters is their sensitivity to electromagnetic emission (EME) as well as the need for galvanic isolation, which is particularly difficult in high-voltage converters [5].

A novel condition monitoring technique that has been researched in recent years overcomes this limitation by utilizing a TSOP, the EL of power semiconductor devices [22]–[29]. As an optical parameter, the EL can be extracted via optical fibers and spatially transmitted to an external sensing circuitry. This intrinsic galvanic isolation provides low sensitivity to EME and simplifies condition monitoring in high-voltage converters [5], [6]. However, previous publication focused on SiC MOSFETs for EL-based condition monitoring whereas the EL of Si IGBTs has hardly been studied in the context of junction temperature sensing. In [22] the EL of Si IGBTs has been investigated but only in terms of current sensing. Therefore, this work analyzes the temperature dependency of the EL of Si IGBTs and presents a dynamic sensing circuitry that extracts junction temperature information with optical fibers and photodiode sensors.

This paper is organized as follows: The first section gives a brief overview of the EL in Si IGBTs and investigates key sensitivities of the EL spectrum. Subsequently, the second section presents the EL-based monitoring solution for online junction temperature sensing. Finally, the sensing approach is experimentally validated by measurements on a commercially available power module.

II. Electroluminescence in Si IGBTs

As a general characteristic of bipolar devices, IGBTs comprise a pn-junction. When this pn-junction is forward biased, i.e., when the IGBT is operated in the first quadrant, electron-hole pairs recombine at the junction [22]. These recombinations are mostly non-radiative due to the indirect bandgap structure of Si [30]. However, a small proportion of the recombinations is accompanied by the emission of

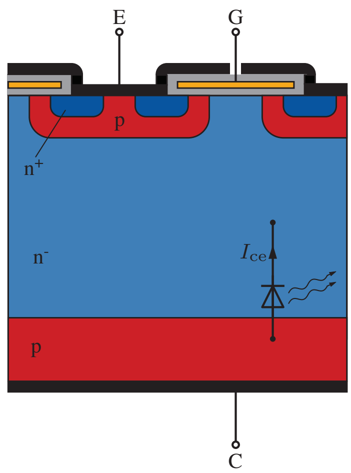

Fig. 1. Simplified cross-section of an IGBT showing the parasitic LED

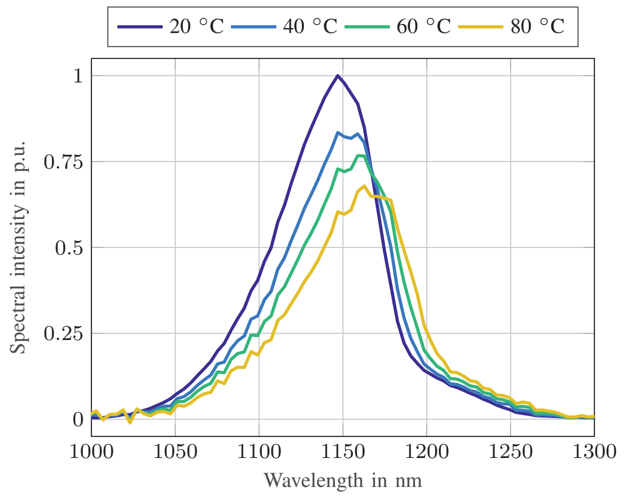

Fig. 2. Typical EL spectra of an IGBT for different junction temperatures

photons, which is known as EL. Therefore, the pn-junction in Si IGBTs behaves like a parasitic light-emitting diode (LED) as depicted in Fig. 1 [22].

A. Spectral Characteristics and Sensitivities

A typical EL spectrum of Si IGBTs consists of a peak in the near-infrared region at around $1150\,\mathrm{nm}$, which is shown in Fig. 2 for various junction temperatures. Light emission at this wavelength corresponds to radiative band-to-band recombinations with a band gap of silicon of about $1.1\,\mathrm{eV}$ at $302\,\mathrm{K}$ [31] and is accompanied by phonon emission [32]–[34]. The band gap E_g of Si is dependent on the temperature T according to [35]:

$$E_\mathrm{g}(T) = 1.16\,\mathrm{eV} - 0.77\,\mathrm{meV\,K^{-1}} \cdot \frac{T^2}{T + 1108\,\mathrm{K}}$$

Due to this temperature dependency of the band gap, the EL peak shifts to higher wavelengths for increasing temperatures [32], as illustrated by the spectra in Fig. 2.

Besides the shift in wavelength, the EL intensity strongly declines with temperature. A possible explanation for this temperature sensitivity is that non-radiative recombinations, such as Shockley-Read-Hall and Auger recombinations, become more dominant at higher temperatures [36]. This temperature sensitivity is the basis for the junction temperature sensing method presented in the next section.

Additionally, the EL intensity depends on the device current I_ce as more injected electron-hole pairs lead to a higher rate of recombinations. Thus, this current dependency must be taken into account when utilizing the EL for junction temperature sensing.

B. Electroluminescence During Converter Operation

In general, the EL occurs in the form of repetitive light pulses during operation of IGBT-based power converters.

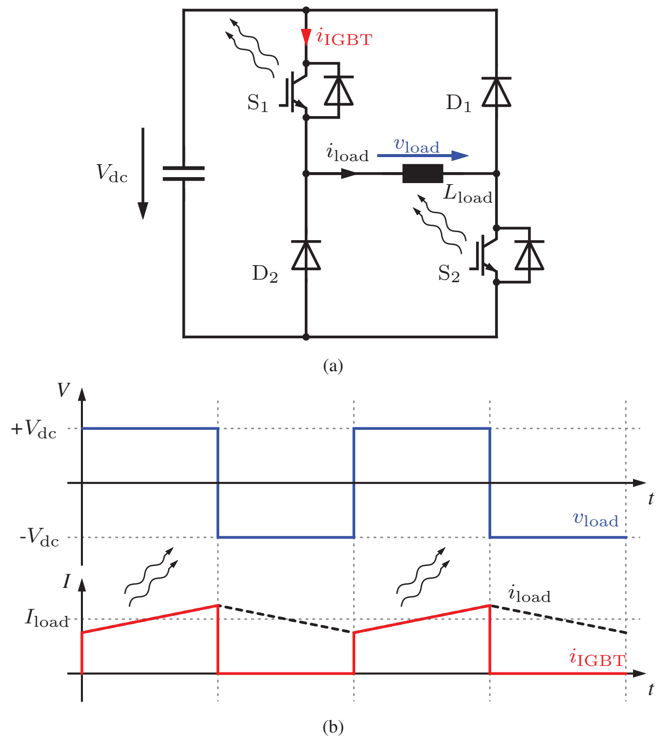

Fig. 3. Equivalent circuit of an asymmetric half-bridge showing the light emission of IGBTs (a) and the corresponding output voltage and current waveforms during steady-state operation (b)

This will be explained in the following by means of an asymmetric half-bridge shown in Fig. 3a. Assuming a positive load current i_load and bipolar modulation, both IGBTs S_1 and S_2 are switched simultaneously resulting in the current and voltage waveforms in Fig. 3b, which shows that the load current is periodically switched between the IGBTs and the diodes. Since the EL occurs for $I_\mathrm{ce} > 0$, the IGBTs emit one light pulse during each switching period. The pulse width is determined by the applied duty cycle whereas the intensity of the light pulse depends on the load current as well as the junction temperature of the respective IGBT. Consequently, the periodically occurring light pulses contain junction temperature information that can be utilized for condition monitoring.

III. Electroluminescence-Based Junction Temperature Sensing

To utilize the periodic EL of Si IGBTs for online junction temperature sensing, this work proposes the monitoring technique depicted in Fig. 4. An optical fiber captures the EL at the edge of an IGBT chip within a power module. Using optical fibers provides intrinsic galvanic isolation and allows placing sensing circuitries at greater distance to the power module. Thus, the EL-based temperature sensing method provides high immunity to electromagnetic interference. Additionally, the intrinsic galvanic isolation

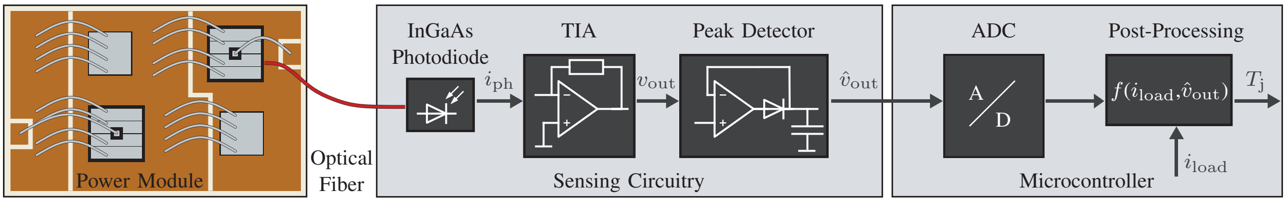

Fig. 4. Overview of the proposed junction temperature sensing technique based on the extraction of the EL via optical fibers and an optical sensing circuitry

simplifies temperature sensing in high-voltage converters, where isolating electrical signals is challenging.

The fiber transfers the EL to an optical sensing circuitry with a photodiode interface that is sensitive to near-infrared emissions and thereby converts the light signal to an electrical signal, i.e., the photocurrent i_{ph}. Due to the weak light emission of Si IGBTs, the photocurrent is only in the range of a few nanoamperes and, thus, has to be amplified. This is done with a transimpedance amplifier (TIA) comprising multiple operational amplifier stages. The output of TIA v_{out} is fed into a resettable peak detector that measures the amplitude v_{out} of each light pulse.

Finally, the output of the peak detector is sampled and post-processed by a microcontroller that calculates the junction temperature of the IGBT based on the sampled value. Since the EL is not only temperature but also current dependent, the post-processing takes the load current i_{load} into account, which is typically measured by additional sensors in power electronic applications. This can be achieved by using look-up tables or analytical expressions. As the light pulses occur every switching period, the sensing solution can extract temperature information with high bandwidth.

For the sake of simplicity, Fig. 4 illustrates the temperature extraction of only a single IGBT. However, the presented technique can easily be extended for power modules with multiple IGBTs by adding additional optical fibers and sensors for each IGBT. Consequently, it is possible to measure the junction temperatures of multiple IGBTs within a power module.

IV. Experimental Evaluation

To validate the proposed monitoring approach, a sensing circuit was designed and experimentally evaluated based on the structure in Fig. 4. In the following, the implementation of sensing circuit and the measurement results are presented.

A. Measurement Setup

The equivalent circuit of the implemented TIA is depicted in Fig. 5. The key element of the sensing circuitry is the optical sensor. Si photodiodes are not suitable for measuring the EL of Si IGBT as they are typically sensitive up to a wavelength of 1100 nm and thereby only capture a fraction of the light emission from Si IGBTs, as can be seen in Fig. 2. Therefore, the circuitry utilizes an InGaAs

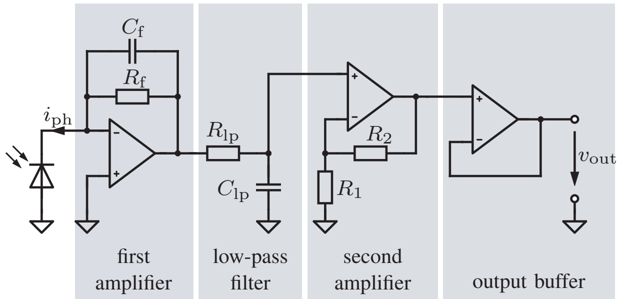

Fig. 5. Equivalent circuit of the implemented TIA

photodiode (G13176-010P, Hamamatsu) providing high sensitivity in the near-infrared spectrum due to the lower band gap of InGaAs compared to Si. As already discussed in Section III, the generated photocurrent is comparatively small such that the input bias current of the TIA should be as low as possible for achieving accurate measurement results. Thus, the operational amplifier ADA4627 is chosen for the first amplifier that exhibits ultra-low input bias current of $5\,\mathrm{pA}$. Additionally, the circuit is supplemented by a passive low-pass filter and a second amplifier stage to reduce noise and achieve a total static gain of approximately $750\,\mathrm{MV\,A^{-1}}$. Finally, an output buffer feeds v_{out} into the resettable peak detector. The second amplifier stage, the output buffer as well as the peak detector comprise general-purpose operational amplifiers while the Texas Instruments development board LAUNCHXL-F28379D was used for the ADC and post-processing.

The sensing circuit was tested on a Si IGBT power module that was configured as an asymmetric half-bridge with an inductive load to generate periodic EL pulses with a duty cycle of approximately $50\,\%$ as depicted in Fig. 3. A closed-loop current control maintained a constant load current I_{load} at a switching frequency of $10\,\mathrm{kHz}$ while a heating plate controlled the temperature of the power module. Within the power module, a fiber-optic cable transferred the EL from the edge of the high-side IGBT to the photodiode of the sensing circuit. The measurement setup is depicted in Fig. 6.

B. Measurement Results

To evaluate the dynamic performance of the developed sensor, an oscilloscope monitored the output voltage of the

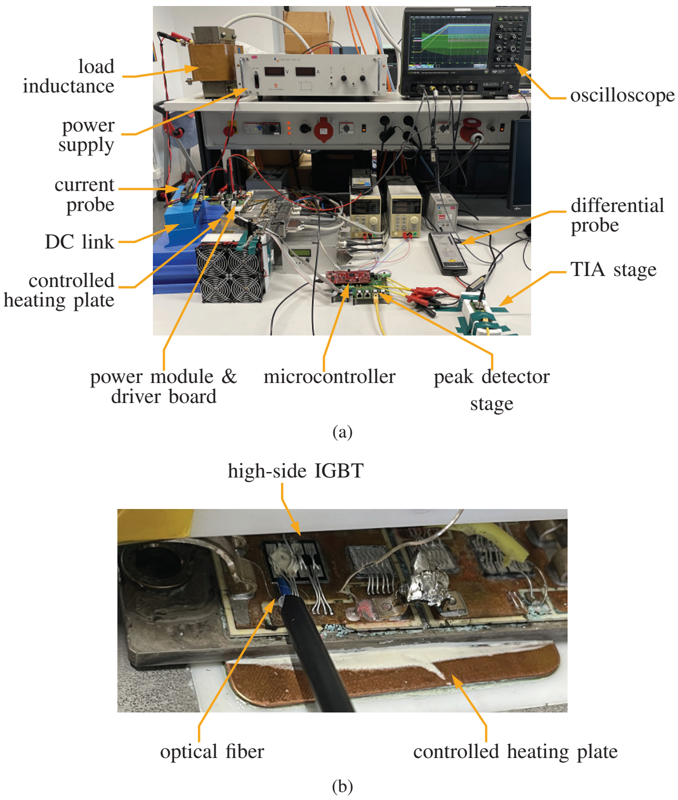

Fig. 6. Measurement setup (a) and light extraction from the edge of the IGBT via an optical fiber (b)

TIA v_{out} during operation. The corresponding measurement results in Fig. 7 show that the sensor is capable of measuring the light pulses with high bandwidth. The output voltage v_{out} exhibits noise due to the small signal-to-noise ratio of photocurrent i_{ph}. However, the output signal can be sampled and averaged over several switching periods to further increase sensor accuracy. This barely degrades the bandwidth of the monitoring solution, as the thermal time constants of power modules are typically decades higher than electrical and optical time constants.

Finally, the monitoring solution was characterized for a wide temperature and current range by measuring the peak voltage $\hat{v}_{\mathrm{out}}$ using the peak detector and the internal ADC of the microcontroller. Fig. 8 shows v_{out} for temperatures between 0 °C and 120 °C and a load current range of 10 A to 50 A. The results confirm the expected negative temperature coefficient of the EL with the strongest sensitivity at high currents and low temperatures. Thus, the measurements prove the feasibility of the proposed monitoring approach for online junction temperature sensing of IGBTs.

V. Conclusion

This paper presented a TSOP-based junction temperature extraction method that utilizes the negative temperature dependency of the EL spectrum of Si IGBTs. Due to intrinsic

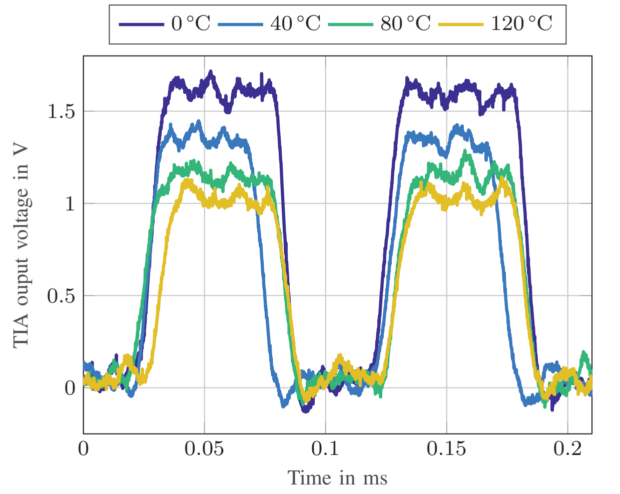

Fig. 7. Dynamic measurements of the TIA output voltage v_{out} for different junction temperatures at a load current of 30 A

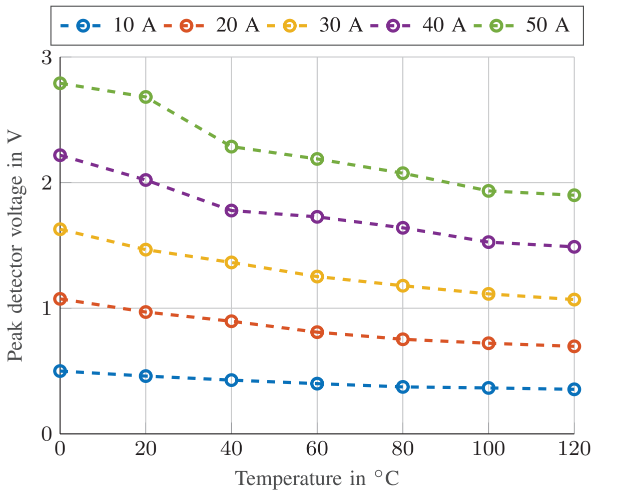

Fig. 8. Measurements of the peak detector voltage as a function of the junction temperature for various load currents

galvanic isolation of EL sensing, e.g., via optical fibers, the sensing method is particularly suitable for applications with high EME and high voltages. The proposed sensing circuitry detects light pulses with high-bandwidth, thus enables online junction temperature sensing. Measurements on an industry-standard IGBT power module validated the temperature extraction capability of the sensing method.

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