Evaluating Different Implementations of Online Junction Temperature Sensing for Switching Power Semiconductors

He Niu
Student Member, IEEE
University of Wisconsin-Madison, WEMPEC
Madison, WI, 53706
hniu@wisc.edu

Robert D. Lorenz
Fellow, IEEE
University of Wisconsin-Madison, WEMPEC
Madison, WI, 53706
lorenz@engr.wisc.edu

***Abstract*—Switching power semiconductor online junction temperature (T_j) sensing is essential for device switching performance evaluation, device switching control, and device lifetime optimization. The contribution of this paper is a detailed evaluation of implementation issues (including circuit invasiveness, hardware integration, signal processing, and so forth) of different online T_j sensing methods. This paper includes T_j sensing methods based on device power dissipation, T_j sensing methods based on the "diode-on-die technology", T_j sensing methods based on device on-state analysis, and T_j sensing methods based on device switching transients. Advantages and limits of these methods are also provided.**

I. INTRODUCTION

The switching/conducting characteristics and power rating of a switching power semiconductor are key factors for power converter hardware integration and thermal management. The junction temperature (T_j) of a switching power semiconductor is one of the key factors that affects their power ratings and switching/conducting characteristics. To realize real-time thermal management and active ΔT_j limit of switching power semiconductors, online T_j sensing is necessary.

The switching power semiconductors used for the commercialized power converters are generally capsulated by power module packages or discrete component packages. Cooling systems are applied to the switching semiconductor packages' surface. At the rated power, the switching semiconductor T_j is higher than the package surface temperature because of the thermal impedance of device package [1]. In transient analysis, the temperature change of package surface is slower compared with the fast power dissipation in the semiconductor chip because of the thermal impedance and heat capacitance of the device package [2] [3]. Thus the switching power semiconductor T_j sensing cannot be easily achieved on the surface of the device package.

[4] [5] [6] reviewed most of the semiconductor T_j sensing methodologies ever studied. The optical methods and physical-contact based methods discussed in [4] can have a 2-dimentional temperature sensing on semiconductor die or substrate, but their invasiveness to device package and slow response time make them ill-suited for online T_j sensing. [5] and [6] pointed out that switching semiconductors' temperature-sensitive electrical parameters (TSEP) can affect their switching/conducting characteristics. By monitoring these switching/conducting characteristics, switching semiconductor T_j can be sensed online without invading the device package.

To study the switching/conducting characteristics of switching power semiconductors, switching loss, conduction loss, and switching speed are the three significant properties that are commonly used to characterize switching power semiconductors [7] [8] [9]. These properties can be largely affected by several TSEPs like MOSFET on-state resistance $R_{DS\text{-}on}$, IGBT on-state collector-emitter voltage drop V_{CE}, MOSFET/IGBT gate turn-on threshold voltage V_{TH}, MOSFET/IGBT transconductance g_{fs}, and so forth [10] [11] [12] [13].

With faster converter switching frequency and more compact hardware integration, switching semiconductor online T_j sensing requires shorter response time, less invasiveness to converter power terminals, and simpler hardware implementations.

Different from the previous studies, this paper specifically evaluates the implementation (hardware invasiveness, hardware integration, signal processing, and so forth) and the sensing bandwidth of different online T_j sensing methods. The T_j sensing methods based on the device power dissipation, the T_j sensing methods based on the "diode-on-die technology", the T_j sensing methods based on the device on-state properties, and the T_j sensing methods based on the device switching transient are discussed in the paper. Comparison of different methods are provided with advantage and disadvantage of each method summarized in a final table.

II. DEVICE POWER DISSIPATION-BASED JUNCTION TEMPERATURE SENSING METHODS

Switching power semiconductor T_j is related to the power dissipation on the semiconductor chip [14]. The power dissipation includes device switching loss and conduction loss that can change each switching cycle [15]. Switching cycle power dissipation and T_j can be estimated iteratively based on the device thermal dynamic model [16].

A. *Methods Based on an Open-loop T_j Observer*

Switching power semiconductor loss depends on the voltage and current on the device, as well as the T_j of the device [17]. In each switching cycle, the estimated device loss $P_{loss\ k}$ has to be updated based on the device voltage v_k (including on-state and off-state voltage) and the device current i_k of this switching cycle, the duty ratio d_k of this switching cycle, and the estimated junction temperature of the latest previous switching cycle T_{j_k-1}. A simple form of the cross-coupled model for power dissipation-based T_j estimation is summarized in (1) and (2), where F is the device loss model and G is the device thermal dynamic model. The accuracy and consistency of the device power dissipation-based T_j estimation largely relies on the accuracy of the loss model F and the thermal dynamic model G in (1) and (2).

$$P_{loss\_k} = F(v_k, i_k, d_k, T_{j\_k-1}) \quad (1)$$

$$T_{j\_k} = G(T_{j\_k-1}, P_{loss\ k}) \quad (2)$$

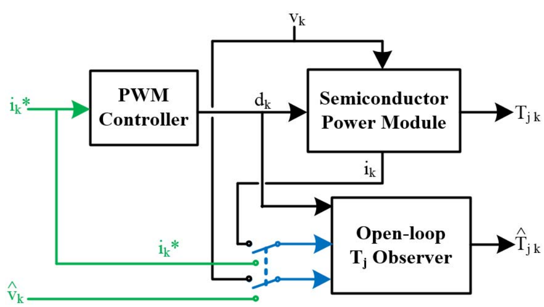

Fig. 1 T_j sensing based on an open-loop T_j observer

An open loop T_j observer based on (1) and (2) can implement this model with or without directly measuring the device voltage, device current, and device duty ratio as shown in Fig. 1. Instead, commanded values (with superscript *) and estimated values (with superscript ^) are used in the loss model F as shown in (3).

$$P_{loss\_k} = F(\hat{v}_k, i_k^*, d_k, T_{j\_k-1}) \quad (3)$$

This method has been applied to several topologies [18] [16]. Experimental results have indicated a 2°C T_j estimation error and a 2 milli-second estimation delay for Mitsubishi Electric 2-in-1 IGBT module [14]. [19] applied this method to Semikron SKM 100GB 123D IGBT module, and a 3.7°C steady state T_j estimation error was found in a prototype test.

Based on (2) and (3) the open-loop T_j observer can be implemented in software, without additional hardware. However the T_j sensing accuracy is dependent on the device loss model F and device thermal dynamic model G. Since no temperature feedback is used in this method, any thermal disturbance can affect the T_j sensing accuracy.

B. *Methods Based on a Closed-loop T_j Observer*

To reject thermal disturbances, a closed-loop T_j observer with feedback signal(s) from the semiconductor power module is required. The feedback temperature signal T_f (module baseplate temperature, direct bonded copper (DBC) temperature, etc.) will be used in the device thermal model G to calibrate T_{j_k} as shown in (4). The block diagram of the closed-loop observer based T_j sensing is shown in Fig. 2.

$$T_{j\_k} = G(T_{j\_k-1}, T_{f\_k-1}, P_{loss\_k}) \quad (4)$$

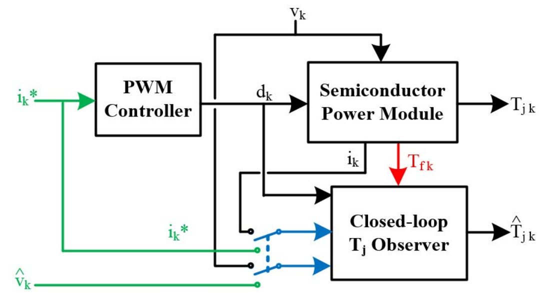

Fig. 2 T_j sensing based on a closed-loop T_j observer

By using the baseplate temperature as the feedback signal, [29] implemented an enhanced Luenburger style T_j observer (closed-loop) on a 150A 1200V Fuji Semiconductor IGBT. In a power cycle test, the IGBT T_j was limited within ±15°C of the desired temperature.

The closed-loop T_j observer rejects thermal disturbance by using temperature feedback. As a result, the disturbance rejection bandwidth of this method is limited by the bandwidth of the feedback temperature signal. The temperature feedback signal can be derived with the temperature sensor galvanically isolated from the power converter. The integration of the temperature sensor, can be invasive (DBC temperature sensor) or non-invasive (baseplate temperature sensor).

Device aging can slightly change the loss model F in (1) [20] [21]. As a result, power dissipation-based T_j estimation methods are degraded by aging of the package and semiconductor chip.

III. DIODE-ON-DIE-BASED JUNCTION TEMPERATURE SENSING METHODS

The forward voltage drop of a p-n junction under a fixed current is known to be temperature sensitive [22]. With modern semiconductor fabrication, manufacturers can embed a temperature sensitive p-n junction on the switching power semiconductor chip and used its properties for online T_j sensing [23] [24] [26]. In [25], the p-n junction sensor was fabricated on the IGBT chip using poly-silicon with insulation, and in [27] this technology was applied to a SiC MOSFET. Since the p-n junction sensor can be considered as a small power rating diode and that the sensor shares the same die with the power semiconductor, this has been referred to as the "diode-on-die technology".

With proper fabrication, the voltage across the diode can be used for IGBT chip online T_j monitoring. In [26], a constant current is supplied through the diode, and the voltage drop across the diode is used for online T_j sensing as shown in Fig. 3. A typical “voltage drop - T_j” correlation for a “diode-on-die technology” sensor can be found in Figure 11 in [26], where the T_j sensitivity was shown to be 6.7mV/°C.

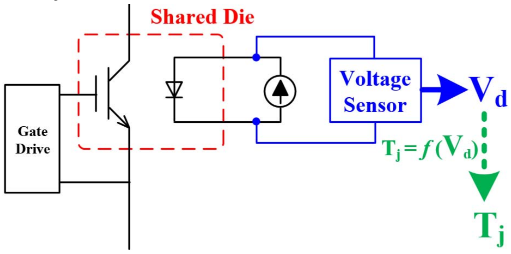

Fig. 3 IGBT T_j sensing based on the “diode-on-die technology”

The “diode-on-die technology” provides a more accurate measurement of semiconductor junction temperature compared with those T_j sensing methods with sensors mounted remotely. Since the size and the volume of the sensor is very small, the thermal dynamics of the sensor can track the semiconductor chip well. In [25], a Fuji 7MBP50RA060 IGBT module using a “diode-on-die technology” sensor had a 2 milli-second response time for an over temperature alarm.

This T_j sensing using a constant current source and voltage measurement [26] can be integrated inside the power module. Though sharing the same die, the p-n junction T_j sensor is isolated from the power semiconductor except for capacitive coupling which can limit its usefulness during transients [27].

Several other limits have been found on the “diode-on-die technology”. Firstly, considering the limited number of stringed diodes used for T_j sensing, the sensing consistency control is challenging. As a result, the performance of the sensors fabricated in the same batch has significant variability [27]. Secondly, the on-chip p-n junction T_j sensor is usually fabricated on a small area on the power semiconductor chip (as shown in figure 8 in [26] and figure 14 in [27]). This location may not reflect the actual thermal gradient on the semiconductor chip. Thirdly, the on-chip p-n junction T_j sensor needs to be connected to the off-chip circuit setup by wire bond or DBC. Since the size of the p-n junction is very small, the position and connection of wire bond or DBC is challenging. The parasitics and contact resistance of the wire bond or DBC has to be carefully controlled as well [28].

IV. Device On-state Properties-Based Junction Temperature Sensing Methods

The semiconductor on-state temperature dependent properties is another option for switching power semiconductor online T_j sensing. Switching semiconductor temperature dependencies, such as the IGBT V_{CE} versus T_j relationship, the MOSFET $R_{DS\text{-}on}$ versus T_j relationship, and the IGBT/MOSFET V_{TH} versus T_j relationship, are usually provided by the manufacturer’s datasheet. With the aforementioned TSEP versus T_j relationships, the semiconductor chip itself can be used as a T_j sensor [5].

[30] proposed in 1971 that with TSEPs, semiconductor on-state properties can be measured for T_j sensing. Different from the conventional operation of a switching semiconductor, a bipolar junction transistor (BJT) is operated on common-base mode, as shown in Fig. 4. Constant current is pulled out from the BJT emitter, and the voltage between BJT base and emitter V_{BE} is correlated to T_j. This method is extended for online BJT T_j sensing in [31], where hardware implementation and data processing is demonstrated in detail. [31] was published in 1991 and a 0.2 second T_j sensing response time was observed.

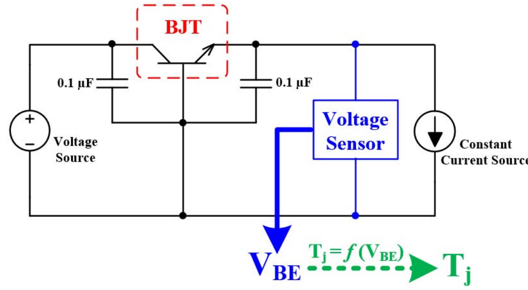

Fig. 4 BJT T_j sensing based on common-base mode V_{BE}. V_{BE} is measured by voltage sensor.

Power MOSFET on-state resistance $R_{DS\text{-}on}$ is known to be T_j dependent, hereby this property is often used for power MOSFET online T_j sensing [32]. Power MOSFET $R_{DS\text{-}on}$ can be digitally calculated online with (1) by measuring the MOSFET on-state voltage $V_{DS\text{-}on}$ and on-state current $I_{DS\text{-}on}$ [33], as shown in Fig. 5. The online calculated $R_{DS\text{-}on}$ will be correlated to T_j based on the power MOSFET “$R_{DS\text{-}on}$ – T_j” relationship.

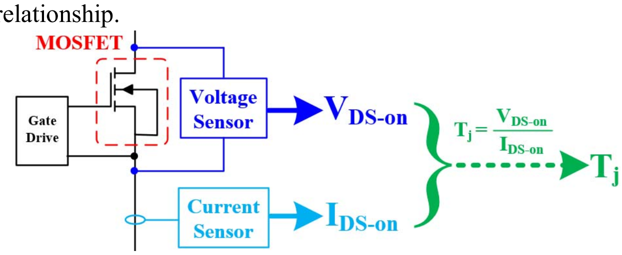

Fig. 5 Power MOSFET T_j sensing based on $R_{DS\text{-}on}$. $R_{DS\text{-}on}$ is calculated by $V_{DS\text{-}on}$ from voltage sensor and $I_{DS\text{-}on}$ from current sensor.

$$R_{DS\text{-}on} = \frac{V_{DS\text{-}on}}{I_{DS\text{-}on}} \tag{1}$$

The IGBT on-state collector-emitter voltage drop V_{CE} is T_j dependent, thus it is widely used for IGBT online T_j sensing [34] [35]. Indeed, IGBT V_{CE} is also on-state current I_{CE} dependent [34], thus measuring I_{CE} is also required for the V_{CE} based IGBT T_j sensing, as shown in Fig. 6. By online measuring V_{CE} and I_{CE}, the IGBT T_j can be correlated in real time based on a three dimensional “V_{CE} – I_{CE} – T_j” relationship like figure 3 in [35]. [36] studied the temperature gradient on the IGBT semiconductor chip when using this V_{CE} based T_j sensing method. [36] claims that the measured V_{CE} and I_{CE} can be correlated to the “current-weighted chip temperature”, the “area-weighted chip temperature”, and the "peak chip temperature" based on the design and geometry of a semiconductor.

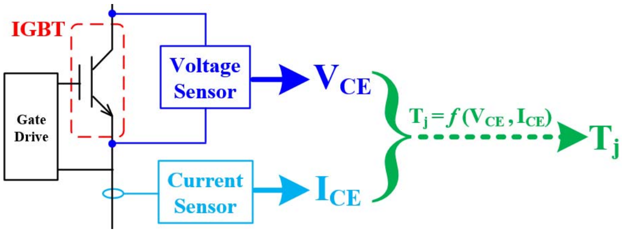

Fig. 6 IGBT T_j sensing based on on-state V_{CE} and I_{CE}. V_{CE} and I_{CE} are measured by voltage and current sensor respectively.

Both the $R_{DS\text{-}on}$ based MOSFET T_j sensing and the V_{CE} based IGBT T_j sensing need to measure the voltage across the device and the current through the device. The voltage sensing is invasively connected to the MOSFET/IGBT power terminals. Consequently, galvanic isolation is required for the voltage sensor. When the switching semiconductor is on, the T_j dependent voltage across the device is often within 1V. When the switching semiconductor is off, the big voltage stress across the device will also be applied to the voltage sensor. As a result, a floating voltage sensor with good resolution and enough voltage stress rating is necessary for the voltage measurement. Current measurement using current transducers can be non-invasive to the power converter.

The on-state properties based T_j sensing is suitable for simple topologies like single ended DCDC converters. With more switching semiconductors used in the converter, high resolution voltage sensing and high voltage isolation for each switching semiconductor can significantly increase the volume of the converter system.

Because the frequency of the converter load current is much slower than the converter switching frequency, the semiconductor current can be taken as constant within several switching cycles. Thus, high bandwidth load current measurement is not required for the device on-state properties based T_j sensing, and the voltage sensing bandwidth will determine the T_j sensing bandwidth for the device on-state properties based T_j sensing [6]. Generally, the voltage sensing bandwidth for the switching semiconductor voltage is above 100kHz [32].

V. Device Switching Transient Properties-Based Junction Temperature Sensing Methods

The T_j dependency of power semiconductor switching transients is another option for online T_j sensing. T_j can be sensed every time the switching power semiconductor is turned on or off. Thus, the maximum bandwidth of the device switching transient properties based T_j sensing depends on the device switching frequency.

The device switching transient properties-based T_j sensing methods can be categorized as methods that measure delay time, methods that measure amplitude, or methods that measure resonant properties.

A. *Methods that Measure Time Duration*

For those methods that measure the time duration of a specific signal, accurate time counters are required.

[37] uses the IGBT gate emitter voltage V_{GE} for online T_j sensing. It was shown that the Miller plateau width of V_{GE} during the IGBT turn-off is T_j sensitive, as shown in figure 1 in [37]. The online measured V_{GE} turn-off Miller plateau time duration can be correlated to IGBT T_j based on the "Miller plateau duration – T_j" relationship, as shown in figure 9 and figure 10 in [37]. Fig. 7 illustrates this method. The resolution of this method is summarized in Table I in [37]. For different IGBT modules, 1°C of T_j variation can cause from 0.8 nanoseconds up to 3.4 nanoseconds' change in Miller plateau duration.

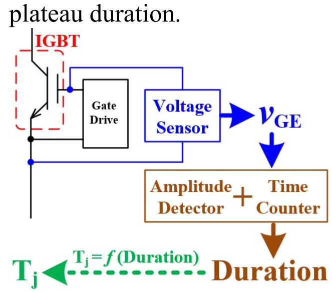

Fig. 7 IGBT T_j sensing based on turn-off Miller plateau duration. Miller plateau duration is measured by amplitude detector and time counter.

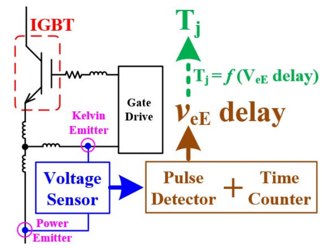

Fig. 8 IGBT T_j sensing based on V_{eE} delay. V_{eE} delay is measure by pulse detector and time counter.

In the IGBT turn-off transient, the induced voltage between the Kelvin emitter and the power emitter (referred to as "V_{eE}") has two spikes with amplitudes of 3V and 5V respectively, as shown in figure 7 in [38]. [38] claims that the delay time between the two spikes (also referred to as "V_{eE} delay time") is IGBT T_j sensitive. The V_{eE} delay time can be measured online and correlated to T_j based on the "V_{eE} delay time – T_j" relationship as shown in figure 8 in [38]. This method is illustrated in Fig. 8. With 1°C of T_j variation, the change of the V_{eE} delay time is 8ns.

For the two methods discussed in [37] and [38], high bandwidth voltage comparators (1GHz minimum) and a high resolution time counters (at least 1ns/step) are required. The method from [37] measures V_{GE}, thus allowing T_j sensing to be integrated into the IGBT gate drive. The method from [38] needs to have access to both Kelvin emitter and power emitter, and in such a case T_j sensing is likely to be embedded inside the power module or placed very close to the power module. Consider that the voltage measurements in [37] and [38] both use the IGBT emitter as voltage reference, for one IGBT chip, its T_j sensing system and its gate drive system can share the same isolated power supply.

B. *Methods that Measure Amplitude*

For those methods that measure the amplitude of a specific signal, accurate analog to digital conversions are required.

[39] proposes that IGBT T_j can be measured using IGBT short circuit current I_{SC}. Simulation and experimental results

indicate that I_{SC} has an adequate T_j sensitivity and linearity. In addition, I_{SC} is not sensitive to device voltage stress, gate drive voltage, or load. By creating a short circuit pulse (hard switching short circuit fault), the I_{SC} pulse amplitude can be used for T_j online sensing, as shown in Fig. 9. [39] also shows that the "$I_{SC} - T_j$" sensitivity is 0.17%/°C. Although I_{SC} can be measured non-invasively using a current transducer, the frequently applied short circuit pulse can increase device degradation as stated in [39]. Accordingly, the frequency and the application strategy of I_{SC} should be carefully considered in the online T_j sensing applications.

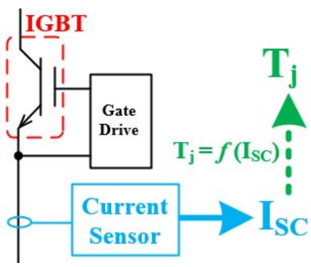

Fig. 9 IGBT T_j sensing based on short circuit current. I_{SC} is measured by current sensor.

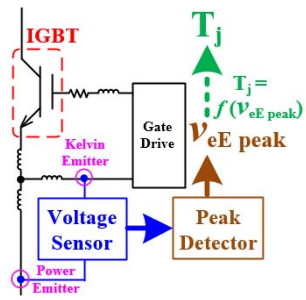

Fig. 10 IGBT T_j sensing based on turn-off V_{eE} pulse peak. V_{eE} pulse peak is measured by peak detector.

Similar to [38], [40] also uses the voltage between the Kelvin emitter and the power emitter V_{eE} for IGBT T_j sensing. Thus, both methods from [38] and [40], for one IGBT chip, its T_j sensing system can share the power supply with its gate drive system, and the T_j sensing system can be integrated inside the IGBT module. In contrast to [38] that studies the delay time between the two pulses during IGBT turn-off, [40] focuses on the one V_{eE} turn-off pulse (the larger one, as shown in figure 3 in [40]). By using either an integration method or a peak detection method, the amplitude of V_{eE} turn-off pulse can be measured and correlated to IGBT T_j based on the "$V_{eE} - T_j$" relationship as shown in figure 5, figure 6, and figure 8 in [40]. Fig. 10 illustrates this method.

[41] and [42] sense semiconductor T_j based on the turn-on gate voltage (V_{GS} for MOSFET, V_{GE} for IGBT). [41] investigated the T_j dependency of the gate threshold voltage V_{TH} and used it for online T_j sensing based on the "$V_{TH} - T_j$" relationship, and a 3mV/°C V_{TH} sensitivity was found experimentally. To measure V_{TH} online, high speed circuitry that synchronously detects the turn-on transient of V_{GS} and drain current is required. To synchronize voltage and current during semiconductor turn-on transient, the circuit design and implementation can be challenging. [42] claims that the integration of an IGBT turn-on V_{GE} transient (referred to as "$\int V_{GE}$") is T_j sensitive. By referring to the "$\int V_{GE} - T_j$" relationship online, T_j can be estimated with a resolution of 84mV/°C. Since only V_{GE} need to be measured, the T_j sensing circuit can be designed inside the gate drive circuit. The methods in [41] and [42] are shown in Fig. 11 and Fig. 12.

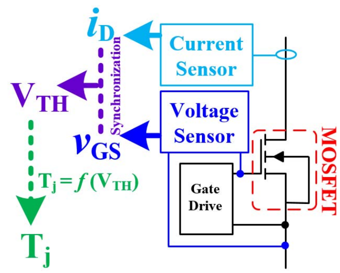

Fig. 11 Power MOSFET T_j sensing based on V_{TH}. V_{TH} is measured by synchronized i_D and v_{GS}.

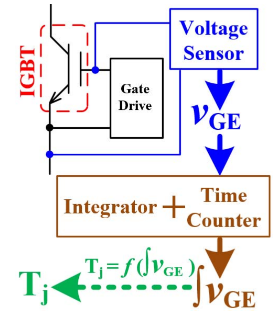

Fig. 12 IGBT T_j sensing based on $\int V_{GE}$. $\int V_{GE}$ is measured by integrator and time counter.

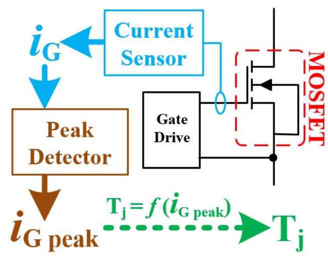

Fig. 13 Power MOSFET T_j sensing based on i_G peak. i_G peak is measured by peak detector.

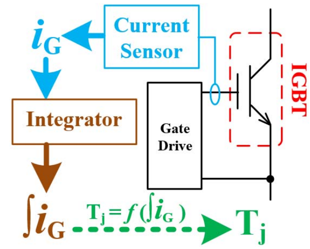

Fig. 14 IGBT T_j sensing based on $\int i_G$. $\int i_G$ is measured by integrator.

Since TSEP's can have an effect on the dynamic interaction between the switching semiconductor and its gate drive system, the gate drive turn-on output characteristics can be T_j sensitive. In that case, the switching semiconductor gate drive turn-on output transient current can be another option for T_j sensing of a power MOSFET [43] or an IGBT [44]. Both [43] and [44] implement the T_j sensing inside the gate drive system, and measure only the gate drive turn-on output transient current i_G, as shown in Fig. 13 and Fig. 14. In such cases, T_j sensing implementation only needs to access to semiconductor gate terminals, and the semiconductor power terminals (MOSFET drain and source; IGBT collector and emitter) are not invasively accessed. [43] proposed a peak detection method applied to i_G so that the online measured i_G peak can be correlated to T_j based on the "$i_{G\ peak} - T_j$" relationship as shown in figure 15 in [43]. A 2.4mA/°C T_j sensitivity was documented in figure 15 in [43]. [44] uses the integration of i_G for T_j sensing based on the "$\int i_G - T_j$" relationship as shown in figure 20 in [44]. Figure 20 from [44] indicated a 0.34%/°C T_j sensitivity.

C. Methods that Measure Resonance Properties

For those methods that measure the signal resonance properties during device switching transients, high bandwidth analog-to-digital conversion (ADC) and online frequency domain analysis are often required.

In [45], [46], and [47], it was demonstrated that the inherent ringing in the output of the converter is dependent upon the junction temperature of the power electronic device. It has been established that the ringing decay time constant in either voltage or current is a direct function of the energy dissipation in $R_{DS\text{-}on}$, which is junction temperature dependent. The transient, high frequency model for the power MOSFET in a boost converter configuration in [45] indicates that the behavior of the power MOSFET during a switching transient can be described as that of an under-damped LCR circuit under nearly step excitation (referred to as 'voltage source- $R_{DS\text{-}on}$-L-C', highlighted in red in Fig. 15). This result shows that the exponential decay of the output voltage ringing is sensitive to the $R_{DS\text{-}on}$ of the MOSFET. The decay envelope of the ringing signal can be used to estimate the temperature of the MOSFET, as depicted in Fig. 15. A 0.16mA/°C T_j sensitivity (load current ringing peak-to-peak value vs. T_j) was found in [45].

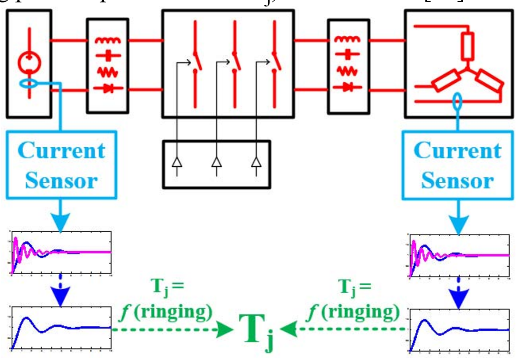

Fig. 15 Power MOSFET T_j sensing based on the 'voltage source- $R_{DS\text{-}on}$-L-C' ringing

Analysis of the measured converter output ringing consists of filtering and system identification [48]. Since the output voltage/current ringing waveform will be distorted by the non-linear characteristics of the circuit (i.e. diode reverse recovery current, gate-drive output ringing, active power supply, etc), the 'voltage source-$R_{DS\text{-}on}$-L-C' ringing needs to be extracted using signal processing techniques. Sampling the ringing signal and fitting it to a second order auto regressive moving average (ARMA) model provide one method of curve fitting. An observer-based ringing extraction method [49] is useful when the $R_{DS\text{-}on}$-damped ringing frequency has a well-behaved, predictable resonant property.

The ringing decay methodology was extended in [50] from the 'voltage source-$R_{DS\text{-}on}$-L-C' resonant model to the 'gate drive-$R_{DS\text{-}on}$-L-C' resonant model (including MOSFET gate-drive, MOSFET intrinsic parameters, and PCB layout parasitics between gate-drive; highlighted in red in Fig. 16). When compared to the ringing discussed in [45], load current ringing generated by the 'gate drive-$R_{DS\text{-}on}$-L-C' resonant model is higher in frequency and its decay time constant is less sensitive to converter load. This high frequency ringing was shown in [50] to be MOSFET junction temperature sensitive, thus it is also feasible for MOSFET junction temperature estimation. The 'gate drive-$R_{DS\text{-}on}$-L-C' ringing based T_j sensing is shown in Fig. 16 with parasitic resonance, intermediate variable, and ringing extraction. A 0.5n-sec/°C T_j sensitivity (ringing time constant vs. T_j) was documented in figure 14 in [50].

The current ringing signals studied in [45] and [50] can be measured on the load or the DC bus. Thus the T_j sensing hardware can be integrated on the converter power input/output side. The ringing signal can be distorted by the switching transient of other semiconductors in the converter. If the ringing signal is distorted and contains multiple harmonics, then Fourier transform analysis to extract the desired ringing signal can require a large amount of numerical computation, which is not suitable for real-time temperature estimation [49].

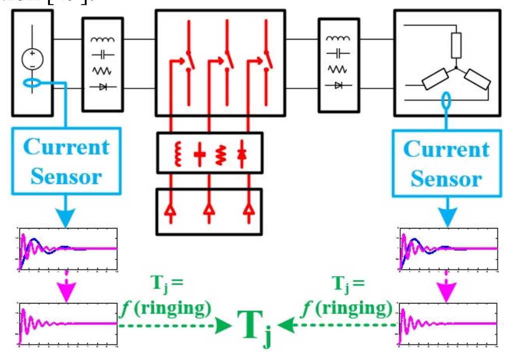

Fig. 16 Power MOSFET T_j sensing based on the 'gate drive- $R_{DS\text{-}on}$-L-C' ringing

VI. CONCLUSIONS

This paper reviews the state-of-the-art methodologies that are feasible for switching power semiconductor online T_j sensing and evaluates them based on metrics such as hardware invasiveness, hardware integration, signal processing requirements and bandwidth capability. The conclusions of this paper are summarized as follows (see also Table I).

- The hardware required for T_j sensing methods using only current measurement is less invasive to the converter power terminals than those using voltage measurement.
- The hardware required for the T_j sensing methods on the gate drive side have lower voltage/current stress and can be integrated inside the gate drive.
- The hardware required for the T_j sensing methods implemented on the converter power circulation side need higher voltage/current ratings.
- The T_j sensing methods based on device power dissipation are the simple to implement, but the accuracy relies on device loss models and thermal dynamic models.
- The T_j sensing methods based on "diode-on-die technology" require fabrication that invades the semiconductor chip but can have simple signal processing and high bandwidth.
- The T_j sensing methods based on device on-state properties are the simple to implement, however the hardware to implement those is more invasive than the hardware to implement T_j sensing methods based on device transient properties.
- The T_j sensing methods based on device transient properties require complex signal processing techniques but can be implemented with minimal or no hardware invasiveness on the converter power circulation side.
- The bandwidth of the T_j sensing methods based on the device on-state properties is limited by the voltage/current sensing response time and signal processing delay.
- The bandwidth of the T_j sensing methods based on the device transient properties is determined by the switching frequency of the semiconductor.

ACKNOWLEDGMENT

The authors wish to acknowledge the motivation provided by the Wisconsin Electric Machines and Power Electronics Consortium (WEMPEC) of the University of Wisconsin-Madison.

TABLE I SUMMARY OF ONLINE JUNCTION TEMPERATURE SENSING METHODS

Method	Ref.	Invading Hardware	Galvanic Connection	Integration	Signal Processing	Sensing Bandwidth	Sensitivity
DEVICE POWER DISSIPATION-BASED JUNCTION TEMPERATURE SENSING METHODS							
Open-loop T_j observer	[14] [16] [18] [19]	No	No	Not required	Simple	Low	
Closed-loop T_j observer	[29]	Depending on sensor	No	Power module inte.	Simple	Low	
DIODE-ON-DIE-BASED JUNCTION TEMPERATURE SENSING METHODS							
Diode-on-die tech.	[23] [25] [26] [27]	Semicond. invading	Capacitive coupling	Power module inte.	Simple	2m-sec response	A few mV/1^{o}C
DEVICE ON-STATE PROPERTIES-BASED JUNCTION TEMPERATURE SENSING METHODS							
BJT V_{BE}	[30] [31]	No	Yes	Load inte.	Simple	0.2sec response	
MOS. R_{ds}-on	[32] [33]	Module invading	Yes	Converter inte.	Simple	Very high	
IGBT V_{CE}	[34] [35] [36]	Module invading	Yes	Converter inte.	Simple	Very high	
DEVICE SWITCHING TRANSIENT PROPERTIES-BASED JUNCTION TEMPERATURE SENSING METHODS							
IGBTMiller Plateau	[37]	No	Yes	Gate drive inte.	Complex	Switching frequency	3n-sec/1^{o}C
IGBT V_{eE} delay	[38]	No	Yes	Power module inte.	Simple	Switching frequency	8n-sec/1^{o}C
IGBT short circuit current	[39]	Converter invading	No	difficult	Simple	High	0.7%/1^{o}C
IGBT V_{eE} peak	[40]	No	Yes	Power module inte.	Simple	Switching frequency	
MOS. V_{TH}	[41]	No	Yes	Gate drive inte.	Complex	Switching frequency	3mV/1^{o}C
IGBT $\int V_{GE}$	[42]	No	Yes	Gate drive inte.	Complex	Switching frequency	84mV/1^{o}C
MOS. i_G peak	[43]	No	No	Gate drive inte.	Simple	Switching frequency	2.4mA/1^{o}C
IGBT $\int i_G$	[44]	No	No	Gate drive inte.	Simple	Switching frequency	0.34%/1^{o}C
Voltage source-$R_{DS\text{-}on}$-L-C	[47] [48]	No	No	Converter inte.	Complex	Depending on signal processing	0.16mA/1^{o}C
Gate drive-$R_{DS\text{-}on}$-L-C	[50]	No	No	Converter inte.	Complex	Depending on signal processing	0.5n-sec/1^{o}C

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