Utilizing the Electroluminescence of SiC MOSFETs as Degradation Sensitive Optical Parameter

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Keywords

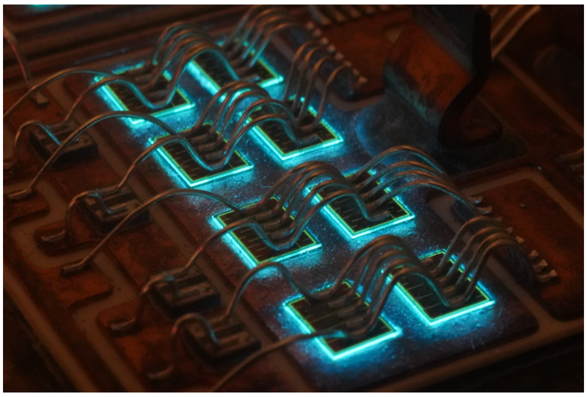
≪Condition Monitoring≫, ≪Reliability≫, ≪Diagnostics≫, ≪Degradation≫, ≪Aging≫, ≪Silicon Carbide (SiC)≫, ≪MOSFET≫, ≪Threshold voltage instability≫, ≪Threshold voltage shift≫

Abstract

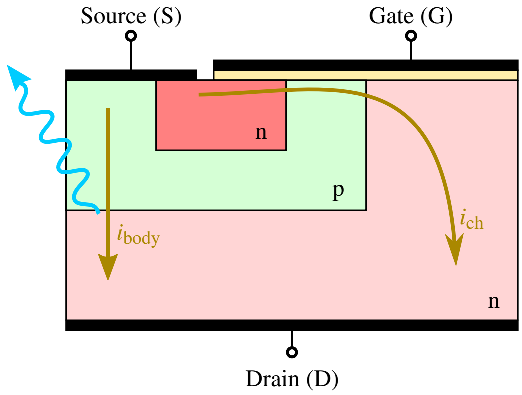
Bias Temperature Instability (BTI) is a major reliability challenge of SiC MOSFETs due to the high defect density of the gate oxide compared to Si MOSFETs. Charge trapping at these defects causes gradual threshold voltage drift and degradation of the on-state resistance, which leads to higher device losses and temperatures. To avoid critical failures, the health state of the gate oxide can be monitored by measuring the BTI-related degradation. This work demonstrates that the electroluminescence (EL) emitted by the body diode of SiC MOSFETs can be utilized as such an aging precursor. As trapped charges at the gate oxide influence the current proportions between the channel and the light-emitting body diode during third quadrant operation, the EL exhibits a sensitivity to BTI that can be sensed as part of online condition monitoring. This paper investigates the EL sensitivity to BTI by means of accelerated aging tests and EL measurements on an industry-standard SiC power MOSFET. The measurement results show a strong increase in the EL intensity for a positive threshold voltage drift, thereby validating the proposed sensing approach.

Introduction

Toward developing highly-integrated power electronic converters and pushing their power semiconductors against electrical and thermal limits, SiC power MOSFETs have widely been adopted in power electronic applications due to their superior physical properties [2]. Moreover, SiC MOSFETs play an increasingly important role in safety-critical applications, such as autonomous vehicles [3] or electrical aircrafts [4], which demands high reliability of the semiconductor components. However, SiC MOSFETs are affected by gate oxide degradation due to the comparatively high defect density of the gate oxide interface compared to conventional Si devices [5]–[7], which may hinder long-term reliability of power electronic converters. One major reliability challenge related to gate oxide degradation is charge trapping at the gate oxide induced by BTI that causes threshold voltage instability [6], [8]. Gradual threshold voltage shifts can increase the on-state resistance of the device and thereby lead to higher losses and temperatures [6], as well as higher thermomechanical stress.



(a)



(b)

Fig. 1: Electroluminescence of a SiC power module (a) and simplified cross section of a power MOSFET (VDMOS) [1] (b)

To monitor the state-of-health of the gate oxide and prevent critical failures, literature proposed online condition monitoring techniques that measure aging precursors during converter operation: Gate charge time [9], gate-plateau voltage [10], [11], body diode voltage [12], [13], and input capacitance [14]. Most of these degradation sensitive *electrical* parameters had already been studied in detail in the context of junction temperature sensing [15]–[17] and have been adopted for degradation sensing. A key challenge in measuring these electrical parameters is their sensitivity to electromagnetic emission (EME) that is particularly challenging in fast switching wide bandgap converters and demands high requirements for electromagnetic compatibility (EMC) of the sensing circuitry [15].

The novel condition monitoring technique that is proposed in this work overcomes this limitation because it is based on a degradation sensitive *optical* parameter, the EL of SiC MOSFETs. As an optical parameter, the EL can be extracted via optical fibers and spatially transmitted to an external sensing circuitry, thus providing low sensitivity to EME due to galvanic isolation. Additionally, the intrinsic galvanic isolation of the EL simplifies condition monitoring in high-voltage converters, where isolating electrical signals requires great effort.

The EL occurs during conduction of the MOSFET body diode [18], as illustrated in Fig. 1. Since the spectrum of the emitted light is dependent on the device current and temperature [19], various monitoring solutions have been proposed in literature that measure the emitted light with photodiode sensors to extract current and temperature information [1], [19]–[24]. While these publications have proven the suitability of EL sensing for high-bandwidth current and temperature sensing, this work shows that EL-based condition monitoring can additionally measure BTI-related threshold voltage drifts. The presented aging precursor is based on the sensitivity of the EL to BTI since charge trapping at the gate oxide influences the proportions of the light-emitting body diode current and channel current during third quadrant operation.

This paper is organized as follows: The first section gives a brief overview of the EL in SiC MOSFETs and investigates key sensitivities of the EL spectrum. Subsequently, the second section analyzes the influence of BTI-induced threshold voltage drifts on the EL and shows how the EL can be used as an aging precursor in terms of condition monitoring. Finally, the sensing approach is validated with an accelerated aging test on a SiC power MOSFET and EL measurements.

Sensitivities of Electroluminescence

The EL in MOSFETs occurs when the internal p-n structure, i.e. the body diode, is forward biased [18]. This is usually the case when the MOSFET is turned off during third quadrant operation ($i_{SD} > 0$) such that minority carriers are injected in the body diode. Due to radiative recombinations of minority carriers, the body diode acts like a parasitic light-emitting diode whose intensity increases with an increasing

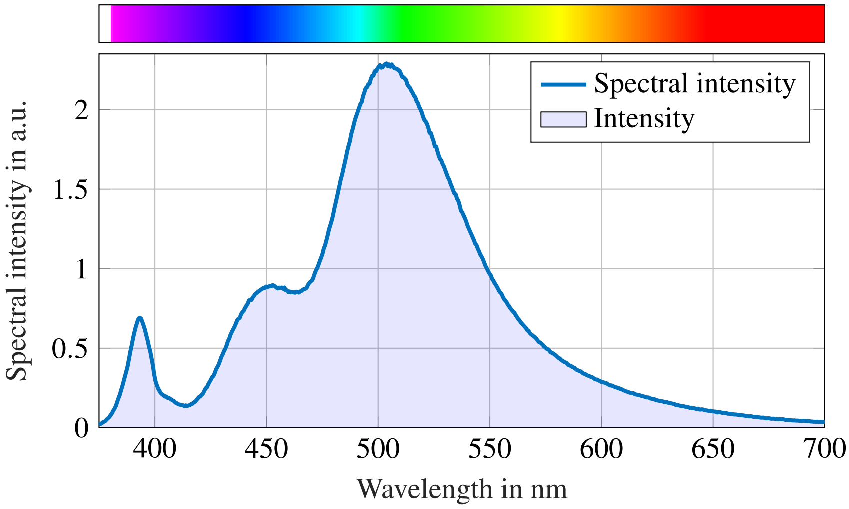


Fig. 2: EL spectra of a 4H-SiC MOSFET body diode

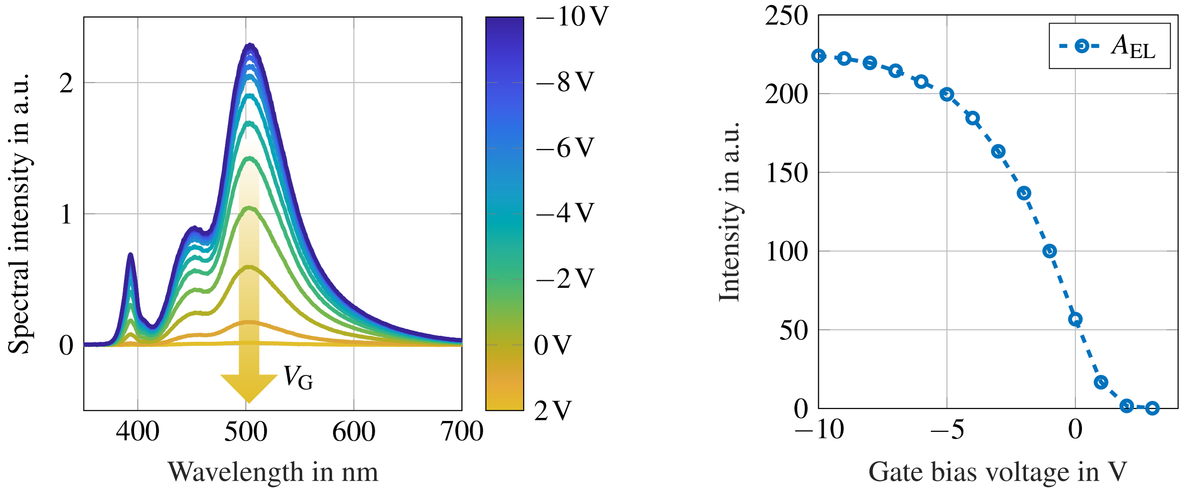
number of minority carriers [25]. The body diode of SiC MOSFETs emits light with sufficient intensity to be used as part of condition monitoring techniques despite the indirect band gap of SiC and the resulting low light emission efficiency.

The EL spectrum of 4H-SiC MOSFETs comprises two major peaks in the visible spectrum [26]–[28] as shown in Fig. 2. While the first peak is located around 390 nm in the ultraviolet region, the second peak is in the blue-green region around 500 nm. The spectral peaks exhibit characteristic current and temperature dependencies which have been analyzed in [1], [20], [24], [29]. Based on these dependencies, different monitoring techniques have been suggested in literature that measure the intensity of the light emission with photodiode sensors to extract temperature and/or current information. For instance, [29] and [22] proposed a current measurement based on the principle that a change in the device current influences body diode current and thus the EL intensity. Besides the device current and temperature dependency of the EL spectrum, the light emission is also sensitive to the gate bias voltage [1].

It is important to understand the influence of the gate bias on the EL because it is based on the same mechanism as the influence of the proposed aging precursor. As illustrated in Fig. 1b, the device current of a MOSFET comprises two components during third quadrant operation: the channel current i_{ch} and the body diode current i_{body}. Only the latter leads to light emission of the body diode. The proportion of these two components strongly depends on the applied gate bias voltage V_{G}. For instance, the lower the gate bias voltage, the higher the share of the body diode current and EL intensity. This can be observed in Fig. 3a showing the spectral intensity of the EL for different gate bias voltages V_{G}: the spectral intensity of the entire spectrum decreases with rising V_{G}. For a more detailed analysis, the spectral intensity is integrated to calculate the total intensity of the light emission A_{EL} as function of V_{G} (compare Fig. 3b). At low and high gate bias voltages, the EL intensity is saturated as the device current flows completely through the body diode or channel, respectively. Thus, the EL exhibits only low sensitivity on V_{G} for these bias conditions because the derivative $\frac{\mathrm{d}A_{\mathrm{EL}}}{\mathrm{d}V_{\mathrm{G}}}$ is low. However, the sensitivity increases when the gate bias causes significant current flows through both the channel and the body diode, e.g., between $V_{\mathrm{G}} = -3\,\mathrm{V}$ and $V_{\mathrm{G}} = 0\,\mathrm{V}$ for the given operating point in Fig. 3.

Electroluminescence as an Aging Precursor for Bias Temperature Instability

BTI is a major reliability challenge of SiC power MOSFETs due to the comparatively high defect density of the gate oxide, especially the gate oxide interface, compared to Si MOSFETs [5]–[7]. Charge trapping at these defects induces positive or negative threshold voltage drifts when a positive or negative gate bias



(a) (b)

Fig. 3: Spectral intensity (a) and intensity (b) for different gate bias voltages V_G measured at $i_{SD} = 10\,A$ and $T_j = 95\,°C$

voltage is applied [6], [30]:

$$V_{G,th} = V_{G,th,0} + \frac{Q_{it}}{C_{ox}} \quad , \tag{1}$$

where $V_{G,th,0}$ is the initial threshold voltage, Q_{it} is the interface trapped charge and C_{ox} is the gate oxide capacitance [6]. BTI-induced threshold voltage variations can be divided into fully reversible drifts that can recover with short recovery time constants and more permanent drifts that are considered as long-term effects and thereby may gradually degrade the electrical performance of the power MOSFET. For instance, a gradual positive drift of $V_{G,th}$ reduces the voltage overdrive $(V_G - V_{G,th})$ during on-state of the MOSFET and thus increases the channel resistance

$$R_{ch} = \frac{L}{W \mu_n C_{ox} (V_G - V_{G,th})} \quad . \tag{2}$$

In (2) μ_n is the electron mobility whereas L and W are the channel length and width, respectively. Such a degradation of the on-state resistance causes higher losses and thermal stress that may ultimately lead to fatigue of the device. By monitoring BTI-sensitive parameters of the MOSFET during operation, abnormal threshold voltage drifts and thus premature aging can be detected.

The EL of SiC MOSFETs is a promising candidate for such an aging precursor. As BTI-induced charge trapping changes the threshold voltage $V_{G,th}$ according to (1), BTI influences the proportions of the body diode and channel current in a similar way as a varying V_G [1]. For a positive drift of the threshold voltage, the EL intensity increases due to lower channel and higher body diode current (and vice versa). Consequently, EL is sensitive to BTI-induced threshold voltage drifts and thereby can be utilized as an aging precursor by monitoring the light intensity during operation.

For this purpose, a gate bias voltage must be applied that provides a high sensitivity of the EL to BTI. As shown in the previous section, the sensitivity is high for bias conditions that allow current conduction through both the channel and the body diode while the EL exhibits almost no sensitivity to threshold voltage variations when the channel is completely closed or opened. Thus, a gate bias voltage with high $\frac{dA_{EL}}{dV_G}$ should be applied for the proposed condition monitoring approach. By repetitively measuring the EL at such a gate bias voltage and a defined operating point for the junction temperature and device current, variations in the light intensity will indicate BTI-induced gate oxide degradation.

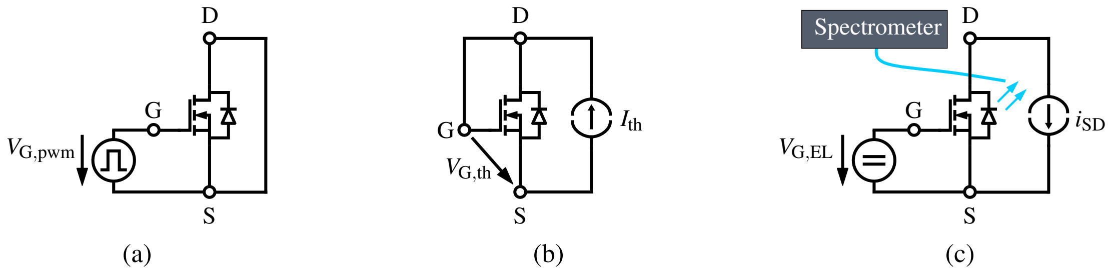


Fig. 4: Equivalent circuit of the accelerated aging test setup (a). After every $18 \cdot 10^8$ switching cycles, the threshold voltage (b) and EL (c) are measured.

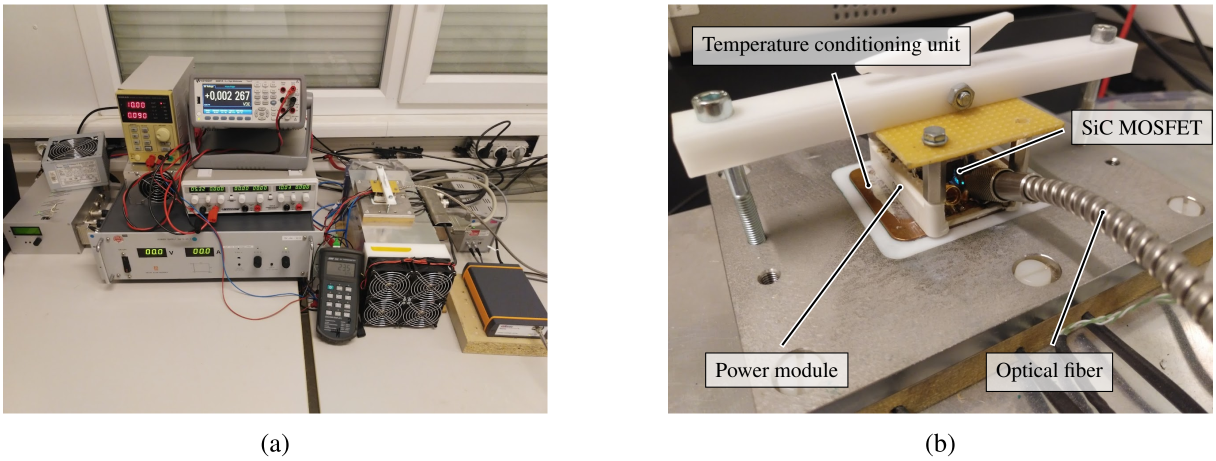


Fig. 5: Measurement setup (a) of the accelerated aging and characterization test as well as an enlarged view (b) of the SiC power module, optical fiber and temperature conditioning unit

Accelerated Aging Test

To verify the feasibility of the proposed degradation sensing method, an accelerated AC aging test, whose technique was proposed in [31], was performed on a trench SiC power MOSFET within an industry-standard power module. For this purpose, the MOSFET was subjected to bipolar gate signals at maximum allowed data sheet voltage levels of 20 V and −10 V at room temperature and a highly elevated switching frequency of 500 kHz while the drain and source terminals were shortened ($V_{DS} = 0\,V$). The equivalent circuit of the aging test setup is depicted in Fig. 4a.

The accelerated aging test was interrupted every hour, which corresponds to $\Delta N_{sw} = 18 \cdot 10^8$ switching cycles, to measure the BTI-induced threshold voltage drift and the EL intensity (compare Fig. 4b and Fig. 4c). The threshold voltage was recorded by a Keysight 34461A digital multimeter that measures the gate-source voltage V_G for an injected drain-source current of $I_{th} = 2\,mA$ while shortening the gate and drain terminals. For reproducible conditions for the threshold voltage measurements, the temperature of the power module was controlled at 45 °C by using type-K thermocouples that were glued to the die surface and a temperature condition unit presented in [32].

After each $V_{G,th}$ measurement, a fiber-coupled spectrometer (AvaSpec-ULS2048CL) measured the EL spectrum for an injected device current i_{SD} of 10 A and a junction temperature T_j of 115 °C. These EL measurements were performed for two gate bias voltages: −10 V and 0 V. As discussed in the previous sections, a gate bias of 0 V is associated with a strong sensitivity of the EL to threshold voltage shifts for the given operating point while almost no sensitivity is expected at −10 V due to the completely closed channel. Thus, the 0 V measurements are meant to validate the proposed aging precursor while the purpose of the −10 V measurements is to proof consistent measurement conditions since the EL intensity is insusceptible to BTI at this gate bias condition. The entire measurement setup is shown in Fig. 5.

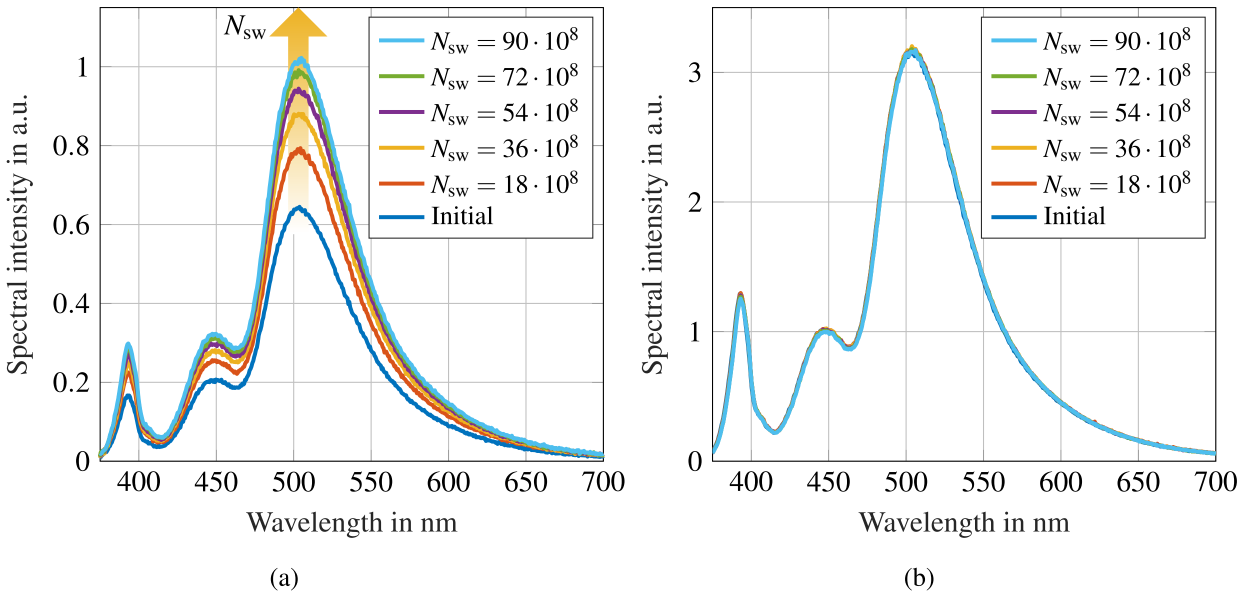


Fig. 6: EL spectra of the SiC MOSFET body diode recorded after each stress cycle at $i_{SD} = 10\,A$ for gate bias voltages of $V_G = 0\,V$ (a) and $V_G = -10\,V$ (b)

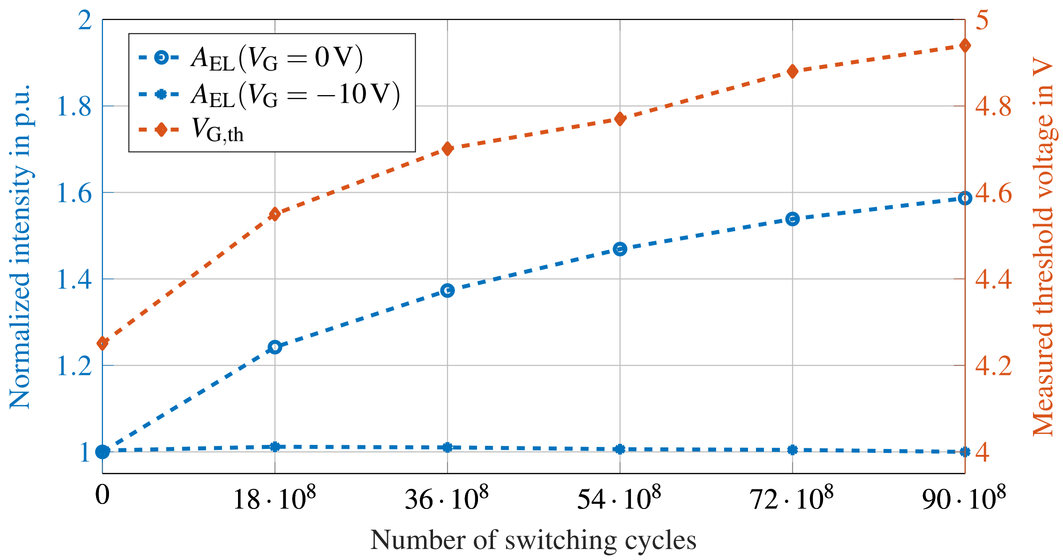


Fig. 7: EL intensity (blue), calculated by integrating the spectral intensity from Fig. 6 and normalized to initial value, and measured threshold voltage (orange) as a function of the number of stress switching cycles (marker: measurement data; lines: linear regression)

The results of the EL measurements are depicted in Fig. 6a and Fig. 6b for $V_G = 0\,V$ and $V_G = -10\,V$, respectively. The spectral intensity of the EL spectra that are recorded at $V_G = 0\,V$ show a significant increase with rising stress cycles N_{sw} compared to the spectral intensity of the initial EL spectrum whereas the EL spectra show almost no change for $V_G = -10\,V$.

To verify that the change of the EL is associated with a threshold voltage drift, Fig. 7 compares the recorded threshold voltage with the total EL intensity A_{EL}. Again, A_{EL} is calculated by integrating the data from Fig. 6 over the entire spectrum and normalizing to the initial value to highlight the relative change caused by the accelerated aging test. The results show a gradual positive threshold voltage shift from $V_{G,th} = 4.25\,V$ to $V_{G,th} = 4.94\,V$ which is clearly correlated with the increase of A_{EL} for $V_G = 0\,V$. This can be explained by trapped negative charges in the gate oxide or at the gate oxide interface that are induced by the applied AC bias stress and cause a rise of the threshold voltage [30]. Since this positive threshold voltage shift increases the proportion of the body diode current and decreases the proportion of the channel current, the EL intensity rises with increasing stress cycles N_{sw}. Consequently, the measurement results verify the sensitivity of the EL to BTI-induced threshold voltage variation and thereby the suitability of the EL as a degradation sensitive optical parameter.

The measurement setup that is used for this work is limited to a laboratory environment and is not suitable for highly dynamic degradation detection in real application. However, previous publications, e.g., [20], have already proven the feasibility of EL-based online condition monitoring by utilizing photodiode sensors and highly dynamic extraction circuits that can easily be adapted for the proposed sensing method. Another challenge is that the presented condition monitoring technique relies on EL measurements at defined junction temperature and device current whose information might not be available in converters. Additionally, the gate bias voltage V_{G} is usually limited to the gate supply voltages. Those depend on the power semiconductor as well as the specific application and thus cannot be chosen arbitrarily as suggested in this work. To cope with these challenges, the proposed degradation sensing method could be integrated in existing EL-based temperature and current sensing techniques by utilizing gate drivers with multiple voltage levels. This would provide junction temperature and current information while one gate driver voltage level that is designated for degradation sensing would allow EL measurements with high sensitivity to BTI-induced threshold drifts.

Conclusion

This work presented a new aging precursor for BTI-related gate oxide degradation utilizing the EL of SiC MOSFETs. Due to intrinsic galvanic isolation of EL sensing, e.g. via optical fibers, the proposed aging precursor is particularly suitable for applications with high EME and high voltages. By conducting accelerated AC aging tests and EL measurements on a SiC power MOSFET, it has been demonstrated that the EL intensity is strongly sensitive to BTI-induced threshold voltage variations and thus can detect critical V_{G} shifts. To maximize the sensitivity of the EL to these threshold voltage drifts, gate bias voltages are applied that neither completely close nor open the MOSFET channel, but allow a current flow through both the channel and body diode. Future work will investigate how this condition monitoring technique can be integrated in existing EL-based current and temperature sensing solutions.

References

[1] L. A. Ruppert, S. Kalker, C. H. van der Broeck, and R. W. De Doncker, "Analyzing spectral electroluminescence sensitivities of SiC MOSFETs and their impact on power device monitoring," in *International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management (PCIM)*, VDE, May 2021.

[2] A. Stippich, C. H. van der Broeck, A. Sewergin, A. H. Wienhausen, M. Neubert, *et al.*, "Key components of modular propulsion systems for next generation electric vehicles," *CPSS Transactions on Power Electronics and Applications*, vol. 2, no. 4, pp. 249–258, Dec. 2017.

[3] F. Blaabjerg, H. Wang, I. Vernica, B. Liu, and P. Davari, "Reliability of power electronic systems for ev/hev applications," *Proceedings of the IEEE*, vol. 109, no. 6, pp. 1060–1076, 2021.

[4] L. Dorn-Gomba, J. Ramoul, J. Reimers, and A. Emadi, "Power electronic converters in electric aircraft: Current status, challenges, and emerging technologies," *IEEE Transactions on Transportation Electrification*, vol. 6, no. 4, pp. 1648–1664, 2020.

[5] R. Singh, "Reliability and performance limitations in SiC power devices," *Microelectronics Reliability*, vol. 46, no. 5, pp. 713–730, May 2006.

[6] T. Aichinger, G. Rescher, and G. Pobegen, "Threshold voltage peculiarities and bias temperature instabilities of SiC MOSFETs," *Microelectronics Reliability*, vol. 80, pp. 68–78, Jan. 2018.

[7] J. Wang and X. Jiang, "Review and analysis of SiC MOSFETs' ruggedness and reliability," *IET Power Electronics*, vol. 13, no. 3, pp. 445–455, 2020.

[8] K. Puschkarsky, T. Grasser, T. Aichinger, W. Gustin, and H. Reisinger, "Review on SiC MOSFETs High-Voltage Device Reliability Focusing on Threshold Voltage Instability," *IEEE Transactions on Electron Devices*, vol. 66, no. 11, pp. 4604–4616, Nov. 2019.

[9] M. Xie, P. Sun, K. Wang, Q. Luo, and X. Du, “Online Gate-Oxide Degradation Monitoring of Planar SiC MOSFETs Based on Gate Charge Time,” *IEEE Transactions on Power Electronics*, vol. 37, no. 6, pp. 7333–7343, Jun. 2022.

[10] Z. Ni, Y. Li, X. Lyu, O. P. Yadav, and D. Cao, “Miller plateau as an indicator of SiC MOSFET gate oxide degradation,” in *2018 IEEE Applied Power Electronics Conference and Exposition (APEC)*, ISSN: 2470-6647, Mar. 2018, pp. 1280–1287.

[11] U. Karki and F. Z. Peng, “Precursors of Gate-Oxide Degradation in Silicon Carbide MOSFETs,” in *2018 IEEE Energy Conversion Congress and Exposition (ECCE)*, ISSN: 2329-3748, Sep. 2018, pp. 857–861.

[12] J. Xin, M. Du, Z. Ouyang, and K. Wei, “Online Monitoring for Threshold Voltage of SiC MOSFET Considering the Coupling Impact on BTI and Junction Temperature,” *IEEE Transactions on Electron Devices*, vol. 68, no. 4, pp. 1772–1777, Apr. 2021.

[13] E. Ugur, C. Xu, F. Yang, S. Pu, and B. Akin, “A New Complete Condition Monitoring Method for SiC Power MOSFETs,” *IEEE Transactions on Industrial Electronics*, vol. 68, no. 2, pp. 1654–1664, Feb. 2021.

[14] M. Farhadi, F. Yang, S. Pu, B. T. Vankayalapati, and B. Akin, “Temperature-Independent Gate-Oxide Degradation Monitoring of SiC MOSFETs Based on Junction Capacitances,” *IEEE Transactions on Power Electronics*, vol. 36, no. 7, pp. 8308–8324, Jul. 2021.

[15] S. Kalker, L. A. Ruppert, C. H. van der Broeck, J. Kuprat, M. Andresen, *et al.*, “Reviewing thermal monitoring techniques for smart power modules,” *IEEE Journal of Emerging and Selected Topics in Power Electronics*, pp. 1–1, 2021.

[16] C. H. van der Broeck, A. Gospodinov, and R. W. De Doncker, “IGBT junction temperature estimation via gate voltage plateau sensing,” *IEEE Transactions on Industry Applications*, vol. 54, no. 5, pp. 4752–4763, 2018.

[17] N. Fritz, M. Friedel, T. A. Polom, and R. W. de Doncker, “Online junction temperature monitoring of power semiconductor devices based on a wheatstone bridge,” in *IEEE Energy Conversion Congress and Exposition (ECCE)*, Oct. 2021, pp. 2740–2746.

[18] J. Winkler, J. Homoth, and I. Kallfass, “Utilization of Parasitic Luminescence from Power Semiconductor Devices for Current Sensing,” in *PCIM Europe 2018; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management*, Jun. 2018, pp. 1–8.

[19] S. Kalker, C. H. van der Broeck, and R. W. De Doncker, “Utilizing Electroluminescence of SiC MOSFETs for Unified Junction-Temperature and Current Sensing,” in *2020 IEEE Applied Power Electronics Conference and Exposition (APEC)*, ISSN: 2470-6647, Mar. 2020, pp. 1098–1105.

[20] J. Winkler, J. Homoth, and I. Kallfass, “Electroluminescence-Based Junction Temperature Measurement Approach for SiC Power MOSFETs,” *IEEE Transactions on Power Electronics*, vol. 35, no. 3, pp. 2990–2998, Mar. 2020.

[21] G. Susinni, S. A. Rizzo, F. Iannuzzo, and A. Raciti, “A non-invasive SiC MOSFET Junction temperature estimation method based on the transient light Emission from the intrinsic body diode,” *Microelectronics Reliability*, 31st European Symposium on Reliability of Electron Devices, Failure Physics and Analysis, ESREF 2020, vol. 114, p. 113 845, Nov. 2020.

[22] S. Kalker, C. H. van der Broeck, L. A. Ruppert, and R. W. De Doncker, “Next Generation Monitoring of SiC MOSFETs via Spectral Electroluminescence Sensing,” *IEEE Transactions on Industry Applications*, pp. 1–1, 2021.

[23] L. A. Ruppert, S. Kalker, and R. W. De Doncker, “Junction-Temperature Sensing of Paralleled SiC MOSFETs Utilizing Temperature Sensitive Optical Parameters,” in *2021 IEEE Energy Conversion Congress and Exposition (ECCE)*, ISSN: 2329-3748, Oct. 2021, pp. 5597–5604.

[24] H. Luo, J. Mao, C. Li, F. Iannuzzo, W. Li, and X. He, “Online Junction Temperature and Current Simultaneous Extraction for SiC MOSFETs With Electroluminescence Effect,” *IEEE Transactions on Power Electronics*, vol. 37, no. 1, pp. 21–25, Jan. 2022.

[25] J. Winkler, J. Homoth, and I. Kallfass, “Electroluminescence in power electronic applications: Utilization of p-n junctions in power semiconductors as unintentional light emitting diodes for current and temperature sensing,” Oct. 2018.

[26] M. Anikin, A. Lebedev, N. Poletaev, A. chuk, A. Syrkin, and V. Chelnokov, “Deep centers and blue-green electroluminescence in 4H-SiC,” Oct. 1993.

[27] A. M. Strel'chuk, E. V. Kalinina, and A. A. Lebedev, "Temperature dependence of the band-edge injection electroluminescence of 4h-sic pn structure," in *Silicon Carbide and Related Materials 2012*, ser. Materials Science Forum, vol. 740, Trans Tech Publications Ltd, Mar. 2013, pp. 569–572.

[28] S. G. Sridhara, L. L. Clemen, R. P. Devaty, W. J. Choyke, D. J. Larkin, *et al.*, "Photoluminescence and transport studies of boron in 4h sic," *Journal of Applied Physics*, vol. 83, no. 12, pp. 7909–7919, 1998.

[29] J. Winkler, J. Homoth, H. Bartolf, and I. Kallfass, "Study on Transient Light Emission of SiC Power MOSFETs Regarding the Sensing of Source-Drain Currents in Hard-Switched Power Electronic Applications," in *PCIM Europe 2019; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management*, May 2019, pp. 1–8.

[30] K. Puschkarsky, H. Reisinger, T. Aichinger, W. Gustin, and T. Grasser, "Understanding BTI in SiC MOSFETs and Its Impact on Circuit Operation," *IEEE Transactions on Device and Materials Reliability*, vol. 18, no. 2, pp. 144–153, Jun. 2018.

[31] P. Salmen, M. W. Feil, K. Waschneck, H. Reisinger, G. Rescher, and T. Aichinger, "A new test procedure to realistically estimate end-of-life electrical parameter stability of SiC MOSFETs in switching operation," in *2021 IEEE International Reliability Physics Symposium (IRPS)*, ISSN: 1938-1891, Mar. 2021, pp. 1–7.

[32] G. Engelmann, M. Laumen, J. Gottschlich, K. Oberdieck, and R. W. De Doncker, "Temperature-Controlled Power Semiconductor Characterization Using Thermoelectric Coolers," *IEEE Transactions on Industry Applications*, vol. 54, no. 3, pp. 2598–2605, May 2018.