Self-Heating and Reliability-Aware “Intrinsic” Safe Operating Area of Wide Bandgap Semiconductors – An Analytical Approach

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Abstract— The emergence of several technology options and the ever-broadening range of applications (e.g., automotive, smart grids, solar/wind farms) for power electronic devices suggest both a need and an opportunity to develop unifying principles to guide the development of wide bandgap (WBG) semiconductors. Unfortunately, power electronic devices are typically evaluated with a variety of elementary figure of merits (FOMs), which offer inconsistent/contradictory projections regarding the relative merits of emerging technologies. Indeed, one relies on the empirical (extrinsic) safe-operating area (SOA) of a packaged device to ultimately assess the performance potential of a technology option. Unfortunately, extrinsic SOA can only be calculated *a posteriori*, i.e., after precise measurement of the fabricated device parameters, making it suitable only for relatively mature technologies. Based on the insights of material-device-circuit-system performance analysis of a variety of idealized WBG power electronic devices (e.g., GaN HEMT, β -Ga₂O₃ MOSFET), in this paper, we analytically derive a comprehensive, substrate-, self-heating-, and reliability-aware “intrinsic/limiting” safe operating area (SOA) that establishes *a priori*, i.e., before device fabrication, the optimum and self-consistent trade-off among breakdown voltage, power consumption, operating frequency, heat dissipation, and reliability. We establish the relevance of the intrinsic-SOA by comparing its prediction with a broad range of experimental data available in the literature. In between the traditional FOMs and extrinsic SOA, the intrinsic SOA allows fundamental/intuitive re-evaluation of intrinsic technology potential for power electronic devices and identifies specific performance bottlenecks and how to circumvent them.

Index Terms — Power Electronics, Safe Operating Area, Self-heating, Reliability, Thermal Resistance, Figure of Merit.

I. INTRODUCTION

An experimentally measured safe operating area (SOA) diagram of a packaged and fully processed device ultimately defines the potential and guides the development of power electronics devices [1]. The SOA of a MOSFET refers to voltage and current limits within which the device can be safely operated. Fig. 1 shows a typical SOA defined by the following limits: on-resistance (R_{on}), breakdown voltage (V_{bd}), maximum current (I_{max}), and maximum power (P_{max}). The SOA deviates from its ideal form due to its thermal and reliability constraints and depends on several device parameters such as ambient temperature (T_{amb}), switching frequency (f),

duty cycle (D), thermal resistance (θ_{th}), etc., which must be considered in order to construct an accurate device SOA. For example, operating at a higher ambient temperature decreases I_{max} , P_{max} , and R_{on} limits, thus decreasing the SOA (Fig. 1).

Despite its importance, it is difficult to reliably calculate the extrinsic SOA of emerging WBG semiconductors because of: 1) immature process technology, 2) unknown material parameters, and 3) lack of fully packaged devices. Therefore, in practice, several simple, easy-to-calculate, material-specific FOMs are used to define and compare the device potential of emerging technologies. For example, Baliga FOM (BFOM) [2] establishes a trade-off between V_{bd} and specific on resistance ($R_{on,sp}$), provided that self-heating (SH) is non-existent. Other popular FOMs defined by Keyes [3], Johnson [4], Huang [5], Shenai [6], etc., variously emphasize self-heating, chip-area, operating frequency, charging time, etc., all in an effort to estimate the quantities of interest.

Unfortunately, it is well known that these traditional FOMs often lead to confusing and inconsistent results regarding the performance potential of various emerging technologies [6]. For example, BFOM suggests β -Ga₂O₃ to be a promising material for power electronics with excellent V_{bd} -to- $R_{on,sp}$ ratio [7], [8]. Yet, self-consistent simulations find the potential of β -Ga₂O₃ to be compromised by SH associated with its poor thermal conductivity (λ) [9]–[11]. Moreover, different material systems (e.g., Si, GaN, SiC) and device configurations (e.g. VDMOS, LDMOS, HEMT) degrade differently as a function of voltage and temperature. Therefore, in practice, technology development generally reverts to detailed and time-consuming material-device-circuit-system simulations or empirically measured parameters based on early-stage products to assess performance [10], [13]–[15]. While resorting to this kind of

Fig. 1. A typical device SOA of a power transistor. It is limited by four quantities: maximum current, maximum power, on-resistance, and breakdown voltage. SOA decreases with increase in the ambient temperature.

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end-to-end analysis is essential for device optimization, the approach might limit the ability to make the right decisions at an early stage of technology development, especially when the transport and thermal models of newly emerging WBG semiconductors, available in TCAD tools, are yet to be vetted against high temperature and high voltage data.

In this paper, we show that recent progress in analytical modeling of the electro-thermal transient response of transistors with multi-layer substrates [16]–[18] as well as the development of generalized multi-hotspot reliability theories of power transistors [19]–[22] allows us to construct an *intrinsic* SOA (*i*-SOA) that balances the multi-dimensional trade-off among V_{bd} , $R_{on,sp}$, f , substrate-aware SH, and reliability. For calculation of *i*-SOA, it is assumed that the material is perfect (i.e., no defects like threading dislocation are present) and that packaging thermal resistance is negligible. Although not a substitute for industry-relevant SOA based on end-to-end modeling and careful qualification of packaged devices, the *i*-SOA obtained here can be used to guard-band vast amount of experimental data reported in the recent literature and to assess the technology potential of WBG semiconductors at the *early stage* of development and identify the probable bottlenecks.

The paper is arranged as follows. In Sec. II, we rederive the trade-off between $R_{on,sp}$ and V_{bd} (Fig. 1, ①) by including the effect of SH and explore its implications. In Sec. III, we derive the expressions for I_{max} and P_{max} (Fig. 1, ②) and evaluate the maximum current for WBG semiconductors based on intrinsic material properties. In Sec. IV, we obtain the substrate-aware *i*-SOA for different WBG semiconductors and systematically compare them with corresponding experimental data. Finally, Sec. V highlights the importance of self-consistent inclusion of transistor degradation. We conclude the paper by discussing the implications of the reliability-aware *i*-SOA for different WBG materials.

II. GENERALIZED R_{ON} AND V_{BD} LIMITS

A. Analytical Model for SH-dependent R_{on} and V_{bd}

Initially proposed by Adler and Westbrook [23], the power electronics FOMs have traditionally focused on reducing $R_{on,sp}$ for a given V_{bd} . From BFOM [2], $R_{on,sp}$ is given by:

$$BFOM = \frac{V_{bd}^2}{R_{on,sp}} = \varepsilon \mu_n E_C^3 / 4. \quad (1)$$

where ε is the permittivity, μ_n is channel mobility and E_C is the critical electric field. BFOM for lateral devices can be written alternatively as [24]:

$$BFOM_{lateral} = \varepsilon \mu_n E_C^3. \quad (2)$$

It is to be noted that μ_n is temperature- and doping-dependent. This dependence not only stems from the ambient temperature but also from SH associated with the operating conditions. The generalized expression is given by [25]:

$$\mu_n(T_{on}) = \frac{\mu_0}{1 + \left(\frac{N_D \xi(T_{on})}{N_{ref}} \right)^\beta} \left(\frac{T_{on}}{300} \right)^{-\gamma}. \quad (3)$$

where T_{on} is the temperature at on-state, N_D and N_{ref} are the doping and the reference doping concentration of the material, μ_0 is the intrinsic mobility at $T=300$ K, $\beta, \gamma > 0$ are empirical exponents and $\xi(T_{on})$ is the ionization ratio of the dopants, calculated from the occupation probability function as (assuming n-type doping):

$$\xi(T_{on}) = \frac{-1 + \sqrt{1 + 4g_D \frac{N_D}{N_C} \exp\left(\frac{\Delta E_D}{kT_{on}}\right)}}{2g_D \frac{N_D}{N_C} \exp\left(\frac{\Delta E_D}{kT_{on}}\right)}. \quad (4)$$

Here, ΔE_D is doping activation energy, g_D is the degeneracy factor, N_C is effective density of state in the conduction band. The optimum doping concentration, N_D and V_{bd} are determined at off-state, at the temperature T_{off} , so that,

$$N_D \xi(T_{off}) = \frac{\varepsilon E_C^2}{2qV_{bd}}. \quad (5)$$

where the critical electric field, given by the empirical relation, $E_C = E_{C0} (1 + \beta' T_{off})$, increases with the temperature. The coefficient β' accounts for the decreased impact ionization rate at higher temperatures. Finally, the on-resistance at a temperature T_{on} , is given by:

$$R_{on,sp}(T_{on}) = \frac{L_D}{q\mu_n(T_{on})N_D \xi(T_{on})}. \quad (6)$$

where L_D is the drift length and $V_{bd} = E_C L_D / 2$ (assuming non-punch-through). Putting Eq. (3), (5), (6), we get:

$$R_{on,sp}(T_{on}) = \frac{4V_{bd}^2}{\varepsilon \mu_0 E_C^3} \left[1 + \left(\frac{N_D \xi(T_{on})}{N_{ref}} \right)^\beta \right] \left(\frac{T_{on}}{300} \right)^\gamma \frac{\xi(T_{off})}{\xi(T_{on})} \quad (7)$$

We will see below that Eq. (7) establishes a novel and essential temperature-dependent generalization of $R_{on,sp}$, and thus Eq. (1). Unlike the traditional FOMs, $R_{on,sp}(T_{on})$ in Eq. (7) *analytically* accounts for excess SH through its impact on mobility, dopant ionization ratio, and impact ionization rate. Previously, one needed to solve multiple equations numerically to include these effects [26]. The idealized bulk parameters in Eq. (7) are easily obtained from online databases (e.g., Ioffe Institute's semiconductor repository [27], first-principle calculation [28]–[30], bulk-measurements [9], [31], [32], and/or TCAD simulations [10], [33]–[35]).

B. Counterbalancing Roles of Self-Heating in $R_{on,sp}$ and V_{bd}

For typical switching speeds ($f > 1$ kHz), $T_{on} \sim T_{off}$ because the thermal time constant of the whole system is large enough to avoid significant cooling during the on-to-off transition. For fully ionized materials with $\Delta E_D \sim kT_A$, Eq. (7) predicts $\xi(T_{off})/\xi(T_{on}) \sim 1$, so that SH increases $R_{on,sp}(T_{on})$ through mobility degradation. However, for materials (e.g. Diamond) with deep dopants (i.e., $\Delta E_D \gg kT_A$), the SH ionizes more dopants, so that $\xi(T_{on}) > \xi(T_{off})$. By Eq. (7), $R_{on,sp}(T_{on})$ is determined by the balance between reduced mobility and increased doping. Similarly, the SH-supported

Fig. 2. (a) While Eq. (1) is constant w.r.t. power, $R_{on,sp}(T_{on})$ (for different power, P) varies depending on the degree of self-heating. As input power increases in a Si device, SH increases as reflected in the curved contour in $R_{on,sp}(T_{on})$. The blue arrows indicate the direction of increasing values (b) $R_{on,sp}(T_{on})$ vs. V_{bd} for Diamond. The solid lines show $R_{on,sp}(T_{on})$ [Eq. (7)] for different applied power. BFOM for Diamond is given as the grey dotted line. At $T=300\text{K}$ and 523K , Eq. (7) matches the numerical results from [26], shown as dashed-dotted lines. The black arrow shows the turn-around for Diamond. Data from [63], [64] are plotted as well for reference.

reduction of impact ionization rate increases the critical field and V_{bd} .

Fig. 2(a) shows that SH reduces the performance potential of Si because of mobility degradation. Remarkably, this is not the case for diamond, as shown in Fig. 2(b). When the power dissipation (P_D) increases from 0 W/mm^2 ($T=300\text{K}$) to 8 W/mm^2 ($T=525\text{K}$), the increased ionization overcomes mobility degradation, leading to improved $R_{on,sp}$ [26]. Diamond benefits from SH because of its higher ionization energy which is otherwise determined by its larger bandgap and its lower dielectric constant (e.g., Boron is an acceptor level with $E_A = 0.37\text{ eV}$ [36]). The increasing conductivity with P_D reduces $R_{on,sp}(T_{on})$. Note that Ref. [26] reaches similar conclusions through numerical simulations at increased ambient temperature, however, our work emphasizes the role of self-heating in achieving similar performance gain even at typical ambient temperature. However, increasing P_D beyond a critical value may lead to a reduction in $R_{on,sp}(T_{on})$ because of increased mobility degradation that eventually counterbalances the beneficial effects of SH (and reduces the gap between the experimental data shown by symbols and the corresponding performance limit). In short, Fig. 2 demonstrates the counterintuitive role of operating conditions in shaping the ultimate performance of power devices and the ability of $R_{on,sp}(T_{on})$ to capture the trend.

C. Substrate-Aware $R_{on,sp}$

According to Eq. (7), the performance of materials such as $\beta\text{-Ga}_2\text{O}_3$, with high E_C , but with low thermal conductivity, may suffer due to SH. Therefore, an ultra-thin layer of $\beta\text{-Ga}_2\text{O}_3$ must be placed on top of a high thermal conductivity substrate (e.g., sapphire [11], diamond [37], AlN [38]) for efficient heat spreading. While a lot of improvements are required in the fabrication techniques of $\beta\text{-Ga}_2\text{O}_3$ FETs to emerge as the high performing power electronics substrate as originally promised, bilayer $\beta\text{-Ga}_2\text{O}_3$ devices should be compared against $R_{on,sp}(T_{on})$ expression (Eq. (7)) to achieve realistic performance prediction of the technology. θ_{th} of the bilayer structures can be estimated using the simple formula provided

Fig. 3. $R_{on,sp}(T_{on})$ [Eq. (7)] predicted for bilayer GaN and $\beta\text{-Ga}_2\text{O}_3$ structures at $P = 1\text{ kW}/\text{mm}^2$ in comparison to the experimental data on bilayer structures. As an example, GaN-on-Silicon (top) and $\beta\text{-Ga}_2\text{O}_3$ -on- $\beta\text{-Ga}_2\text{O}_3$ device (bottom) have been shown here. Data taken from [39], [40].

in Appendix A. Fig. 3 shows the comparison between the experimental data of a GaN-on-Si device [39] and a $\beta\text{-Ga}_2\text{O}_3$ -on- $\beta\text{-Ga}_2\text{O}_3$ device [40]. In both cases, the generalized $R_{on,sp}$ (Eq. (7)) anticipates the experimental trends better than BFOM and suggests that the devices may already be performing close to their intrinsic limits, further indicating that BFOM represents an overly optimistic metric for nontraditional WBG materials.

In practice, the rise of the junction temperature is limited by packaging and other considerations, suggesting an upper limit of power (P_{max}) and current (I_{max}) that can be sustained by a technology. We will discuss this limiting current performance in the next section.

III. GENERALIZED I_{max} AND P_{max} LIMITS

A. Analytical Derivations

Since the device mobility degrades with increasing temperature, the device junction temperature is required to be well below the maximum junction temperature ($T_{j,max}$) to maintain proper functionality. In other words, for a given material, geometry, structure, and package (i.e., given θ_{th}), the maximum allowable power dissipation (P_{max}) can be represented as:

Fig. 4. (a) (Left) Normalized I_{max} metric for WBG materials at $\Delta T_{max} = 150\text{K}$. (Right) $\beta\text{-Ga}_2\text{O}_3$ channel layer on various substrates (Sapphire, SiC, Diamond). The performance (i.e., I_{max}) can be improved by depositing $\beta\text{-Ga}_2\text{O}_3$ on higher thermal conductivity substrates. The arrow indicates increasing performance of $\beta\text{-Ga}_2\text{O}_3$ FETs. (b) Comparison of on-current predicted by Eq. (11) with that of experimental data.

$$P_{max} = \frac{\Delta T_{max}}{\theta_{th,j-c} + \theta_{th,c-a}} \quad (8)$$

where ΔT_{max} is the maximum temperature rise, ($\Delta T_{max} = T_{j,max} - T_{amb}$), T_{amb} is the ambient temperature, $\theta_{th,j-c}$ and $\theta_{th,c-a}$ are junction-to-case and case-to-ambient thermal resistances. P_{max} can be directly linked to the maximum current rating (I_{max}) if only the conduction loss is considered. To determine I_{max} for a device, $T_{j,max}$ is fixed, in contrast to the procedure for $R_{on,sp}$ derivation in Sec. II, where ΔT was determined by P . To determine the intrinsic limiting performance, we neglect $\theta_{th,c-a}$ (can vary with different package configurations) and switching loss (may vary with different gate drive circuits and switching conditions [5]). Therefore, the maximum allowable current density can be written as:

$$I_{max} = \sqrt{\frac{\Delta T_{max}}{\theta_{th,j-c} R_{on}}} \quad (9)$$

where I_{max} is the maximum allowable current in a device at ΔT_{max} . Let us assume $\theta_{th,j-c} = (W\lambda_{sub}S)^{-1}$, where W is the device width, λ_{sub} is the substrate thermal conductivity, and S is the shape factor [41]. In practice, one can easily obtain the shape factor for a technology from thermal modeling and/or experimental measurements [16]-[17]. Note that effective $\theta_{th,j-c}$ (for the packaged chip) can change with duty cycle and frequency, as discussed in Section IV. For a lateral device, the normalized I_{max} can be written as:

$$\frac{I_{max}}{W} = \sqrt{D_{dr}} \sqrt{\frac{\lambda_{sub} S \Delta T_{max}}{R_{on,sp}(T_{on})}} \quad (10)$$

where D_{dr} is the drift region thickness. It can be easily adapted for vertical devices by interchanging D_{dr} with the gate length. For I_{max} calculations, $T_{on} \equiv T_{j,max}$. Substituting the $R_{on,sp}(T_{on})$ as in Eq. (7), we obtain a metric to compare the maximum current for various WBG semiconductors, as:

$$\frac{I_{max}}{W} \propto \sqrt{\frac{\varepsilon \mu_n E_C \lambda_{sub} S \Delta T_{max}}{\frac{\xi(T_{off})}{\xi(T_{on})} \left(\frac{T_{on}}{300}\right)^{\gamma}}} \quad (11)$$

The corresponding generalization of I_{max} (Eq. (11)) provides a new limit that explicitly accounts for the first time, the effect of temperature-dependent mobility, shape factor, and incomplete ionization.

B. Substrate-Aware I_{max} in lateral devices

The effect of SH is more severe in lateral devices compared to vertical devices, and hence lateral devices are compared for demonstration in various WBG materials. The device dimensions and basic parameters used for calculations are tabulated in Appendix D. θ_{th} is calculated considering 3D thermal spreading (formula provided in Appendix B). By alternating the corresponding λ for channel and substrate material, the I_{max} FOM at fixed ΔT_{max} (150 K here) for

Fig. 5. β -Ga₂O₃ FETs on various substrates. (a) Increased current in β -Ga₂O₃ FETs as predicted by I_{max} equation (eq. 11), [10]. (b) Decreased junction temperature, resulting from the use of higher thermal conductivity substrates.

various WBG materials is easily calculated. Fig. 4 (a) shows the calculated values normalized to the value of Si, including the bulk material (left half). For bulk materials, at the same ΔT_{max} GaN and SiC have four times larger I_{max} than Si. Bulk β -Ga₂O₃, however, performs worse than GaN and SiC. As shown in Fig. 4 (b), the I_{max} values predicted by Eq. (11) for β -Ga₂O₃, reproduces the experimentally obtained current for β -Ga₂O₃ in Ref. [42], Ref. [43], and Ref. [44] for different geometric configurations. The prediction, by Eq. (11) for Ref. [44] was slightly lower compared to the experimental data, which could be due to the uncertainty (10 - 20% [45]) in the Raman thermography technique used to obtain the peak channel temperature.

To improve I_{max} (right half, Fig. 4(a)), we consider β -Ga₂O₃ on various substrates with higher thermal conductivity. The device geometry of the bilayer structure (β -Ga₂O₃ on various substrates) has been tabulated in Appendix D. The I_{max} metric assigns β -Ga₂O₃ a lower rank than other WBG materials due to its low thermal conductivity. The bottleneck of the low thermal conductivity can be alleviated by stacking β -Ga₂O₃ on high thermal conductivity substrates. This is achieved by fabricating β -Ga₂O₃ FETs on Sapphire and Diamond as shown in Fig. 5(a). As predicted by I_{max} , high current is observed at the same gate overdrive for β -Ga₂O₃ FETs on Sapphire and Diamond. This is because of the reduction in junction temperature, as revealed by thermo-reflectance measurements and TCAD simulations (Fig. 5(b)) [10]. Therefore, qualitatively β -Ga₂O₃ can be a material of choice for power electronics, only if appropriate thermal shunts or other cooling systems are employed.

IV. SELF-HEATING AWARE INTRINSIC SOA FOR WBG SEMICONDUCTORS

The substrate- and SH-aware expressions obtained in the previous sections can now be used for obtaining the i -SOA of a power device. Since frequency dependence is an important consideration for power transistors, the effect of transient thermal resistance (Z) needs to be considered. At $T_{amb} = 300$ K, by setting $T_{j,max} = 450$ K, P_{max} can be determined using the following relation:

$$P_{max} = \frac{T_{j,max} - T_{amb}}{\theta_{th} \times Z_m(t_{on})} = I_D \times V_D \quad (12)$$

Fig. 6. i -SOA predicted for various bulk WBG materials based on Eqs. 10-13.

θ_{th} is the DC thermal resistance, $Z_m(t_{on}) < 1$, is the normalized transient thermal impedance, t_{on} is the pulse duration ($t_{on} = D\zeta$, ζ is the period, D is the duty cycle). Considering multiple stages of equivalent RC-time constants due to package, submounts, heat sink, PCB, etc., one can write [17], [18]:

$$Z_m(t_{on}) = D + (1 - D) \sum_i \frac{\theta_{th,i}}{\theta_{th,tot}} C_i(D, \zeta) Z_{0,i}(t_{on}) \quad (13)$$

$$\text{with } C_i(D, \zeta) = \frac{1 - \exp\left(-\frac{(1-D)\zeta}{\tau_{th,i}}\right)}{1 - \exp\left(-\frac{\zeta}{\tau_{th,i}}\right)}.$$

where index i stands for a certain stage of RC circuit ($i = 1$ is the chip itself), $C_i(D, \zeta)$ is a correction function that depends on τ_{th} of each stage. Z_0 is the transient thermal impedance for a single pulse expressed as $[1 - \exp(t_{on}/\tau_{th})]$, where τ_{th} ($\tau_{th} = \theta_{th}C_{th}$) can be calculated by the parameters given in Appendix D. The derivation of Eq. (13) is provided in Appendix C. *This is the first closed-form analytical expression for arbitrary complex package structure subjected to pulses of arbitrary duty cycle that considerably simplifies the calculation of i -SOA.* Knowing $Z_m(t_{on})$, the current limit can be found from the following expression:

Fig. 7. i -SOA predicted for bilayer substrates. β -Ga₂O₃ on various substrates (native β -Ga₂O₃, Sapphire, SiC, Diamond) are shown as an example. Temperature-dependent R_{on} has been shown in red dashed lines.

$$I_{max} = \sqrt{\frac{T_{j,max} - T_{amb}}{\theta_{th} Z_m(t_{on}) \times R_{on}}}. \quad (14)$$

Using Eqs. 7, 11-14, the i -SOA for different bulk WBG materials (Fig. 6) and bilayer structure (Fig. 7, β -Ga₂O₃ as an example) can be calculated analytically by assuming $t_{on} = 10$ ms and $D = 0.5$ for a standalone device ($i = 1$). Using the same procedure, the performance and i -SOA of other device systems (e.g. GaN-on-Si, GaN-on-SiC, etc.) can be easily evaluated. In Fig. 6, some of the materials (except GaN and β -Ga₂O₃) show a similar DC and AC response because of a low time constant. It is evident that device SH plays an important role in determining performance. Because of larger θ_{th} , β -Ga₂O₃ gains more i -SOA in AC operations, compared to DC condition. We reach similar conclusions for other WBG materials as well. In Fig. 6, materials with larger λ_{sub} have larger i -SOA, as expected. Thus, the i -SOA obtained here gives a holistic device-circuit-system perspective of WBG semiconductor performance.

V. RELIABILITY-AWARE SOA

A. Reliability-Aware $R_{on,sp}$

Several previous works emphasize the importance of defining a reliability-aware generalization of the SOA [46], [47]. The reliability-aware SOA is defined in various ways viz., voltage-dependent HCD stress SOA [48], thermal SOA [49], catastrophic failure SOA [50], etc. Although achievable for extensively studied devices (such as Si LDMOS), these SOAs are difficult to be determined for emerging WBG materials. Therefore, we propose a reliability-aware i -SOA that can be analytically obtained for a very well-researched device like Si LDMOS, as well for state-of-the-art emerging WBG material-based devices like Diamond and β -Ga₂O₃.

We note that $R_{on,sp}$ degrades over stress time (t) as bulk and interface traps are generated during device operation. These traps scatter electrons and reduce mobility. The exact form of the mobility degradation depends on specific material; however, it can be simply expressed in the phenomenological Sun-Plummer form [51]:

$$\mu_n(T_{on}, t) = \frac{\mu_n(T_{on}, t = 0)}{(1 + \alpha \Delta N_{IT}(t))} \quad (15)$$

and time evolution of $\Delta N_{IT}(t) \sim f(t/\tau)$ depends on the voltage- and temperature-dependent scaling factor, τ [52], [53]. The precise functional form (e.g., power-law, exponential, sigmoid, etc.) of N_{IT} generation depends on the material of choice. The reliability factor appears as a multiplicative derating factor [54]–[56] in Eq. (7) for $R_{on,sp}$, namely:

$$R_{on,sp}^*(T_{on}, t) = R_{on,sp} \times T_f \times R_f(t) \quad (16)$$

where T_f is the temperature correction factor, and R_f is the reliability correction factor, given as:

$$T_f = \left[1 + \left(\frac{N_D \xi(T_{on})}{N_{ref}} \right)^\beta \right] \left(\frac{T_{on}}{300} \right)^\gamma \frac{\xi(T_{off})}{\xi(T_{on})} \quad (17a)$$

Fig. 8. (a) Schematic of the Si LDMOS used in the study. (b) TCAD calibration of the temperature dependent HCD characteristics of the LDMOS. (c) The 2D plots showing the Si/SiO₂ interface and trap generation in the interface, in a Si LDMOS. (d) ΔN_{IT} with increasing stress time at different temperatures. (e) Reliability-aware $R_{on,sp}$ or $R_{on,sp}^*$ predicted for Silicon power devices (LDMOS) (f) Reliability-aware i -SOA predicted for LDMOS device at different interface trap concentrations.

$$R_f(t) = (1 + \alpha \Delta N_{IT}(t)). \quad (17b)$$

The reliability of power transistors depends on various degradation mechanisms (e.g., HCD [20], BTI [57], the inverse piezoelectric effect [58], etc.) with temperature and voltage-dependent degradation rates. The localized generation of N_{IT} in a multi-hotspot power transistor is phenomenologically written as [19], [21]:

$$\Delta N_{IT}(t) = \frac{At^n}{1 + Bt^n} \quad (18)$$

where the coefficients A and B may have positive or negative temperature coefficients and power-law or exponential voltage acceleration factors.

B. Reliability-aware intrinsic SOA

For an illustrative example, the role of trap-induced degradation is analyzed with TCAD simulations on Si LDMOS (Fig. 8 (a)) [59]. The LDMOS has been electrically stressed to analyze the Hot Carrier Degradation (HCD), as shown in Fig 8(b) [19]. In Si transistors, it is well known that $\Delta N_{IT}(t)$ reduces at higher temperature [56] (Figs. 8(c) and 8(d)) due to reduction of impact ionization rate due to increased phonon scattering. By including reliability aspects connected to $\Delta N_{IT}(t)$ in the $R_{on,sp}$ expression, one can project device performance over prolonged operation. This is shown in Fig. 8(e), where $R_{on,sp}^*(T_{on}, t)$ for Si LDMOS is calculated with $\Delta N_{IT}(t)$ after certain stress time. As expected, $R_{on,sp}^*(T_{on}, t)$ increases due to stress but, at the same time, SH reduces

$\Delta N_{IT}(t)$ (at a fixed stress time) in this case. This is shown by the dotted (solid) line that represents the impact of $\Delta N_{IT}(t)$ on $R_{on,sp}(T_{on})$ without (with) thermal effects. The increasing SH reduces HC-induced $\Delta N_{IT}(t)$, with a small improvement in $R_{on,sp}^*(T_{on}, t)$. I_{max} accounts for $\Delta N_{IT}(t)$ through $R_{on,sp}(T_{on})$ and the newly calculated I_{max} can be used to obtain a Reliability-aware i -SOA (Fig. 8(f)). As the stress time increases, $N_{it}(t)$ increases, thus decreasing the mobility (captured using Eq. (17)), leading to increased $R_{on,sp}$, decreased I_{max} , and closure of i -SOA. Following similar approaches, i -SOA can be obtained for other WBG semiconductors as well, provided their stress-dependent N_{IT} is known either by TCAD simulations or experiments.

VI. DISCUSSION AND CONCLUSIONS

In this paper, we have presented an analytical model (Eqs. 7, 11-14) to calculate the i -SOA for modern power electronic devices that accounts for the SH effect and trap-induced degradation and compared the results with a broad range of experimental data published in the recent literature related to emerging WBG materials, such as Ga₂O₃. We have demonstrated that starting with the generalization of BFOM, one can get the device i -SOA by carefully considering the SH effects through substrate-aware θ_{th} , temperature-dependent mobility, incomplete ionization, and trap generation rate. To account for the substrate-aware SH, accurate modeling of θ_{th} is essential, which has been achieved using simple, but robust θ_{th} formula (Appendix A and B). These generalizations allow calculating more realistic intrinsic device i -SOA, which was previously possible only through end-to-end modeling based on device-specific parameters and/or careful measurement of packaged devices.

1. The temperature- and reliability-aware i -SOA reveals that intrinsically diamond is the best possible candidate at high temperature (here $T_{j,max} = 450$ K) among the WBG materials surveyed here. The i -SOA provides the new insight that Diamond would benefit from SH and its performance would increase with increasing P_D , but only until all its dopants are fully ionized, after which the temperature-dependent mobility degradation dictates the performance limit.
2. Similarly, from the perspective of i -SOA, GaN and SiC have comparable performance, with V_{bd} in the kV range. In practice, the material quality may further limit the empirical SOA for these materials.
3. Moreover, with proper thermal management (high thermal conductivity substrates, cooling, etc.), i -SOA suggests that β -Ga₂O₃ FETs may be able to deliver performance comparable to GaN and SiC.

In practice, nonideal effects, such as threading dislocations, interfacial thermal resistance, the choice of substrate, etc. may make the extrinsic SOA somewhat (or substantially) different. Regardless, based on application-specific requirements on

power dissipation and reliability, the *i*-SOA provides a unifying conceptual framework to assess the early-stage experimental data and to define the accurate merits and fundamental bottlenecks of emerging WBG technologies for specific power electronics applications long before the devices are ready to be packaged and tested.

APPENDIX

A. Determining Thermal Resistance of a Bilayer Structure

The self-heating at the device level (i.e., $\Delta T = P_D \theta_{th}$) is determined by calculating the θ_{th} associated with the structure. While the formula and techniques of determining θ_{th} of a bulk substrate is well established, θ_{th} of a multi-layered device is more complicated due to the change in the heat spreading angle in different layers.

For a bulk substrate, the simplest approach of calculating θ_{th} is to assume that heat spreads at a constant angle, ω (consider $\omega \sim 45^\circ$, for simplicity). For a disk-shaped heat source of radius, a , thermal conductivity, λ , on a substrate of thickness, ℓ , as shown in Fig. A1(a), θ_{th} can be obtained as [60]:

$$\theta_{th, \text{single layer}} = \frac{1}{\lambda \pi a} \frac{\ell}{(a + \ell \tan \omega)} \quad (A1)$$

Now, let us consider a bilayer substrate with the thickness of the top layer, ℓ_1 and bottom layer, ℓ_2 respectively. The heat spreading angle and the thermal conductivity of the top layer is given as ω_1 and λ_1 and correspondingly ω_2 and λ_2 for the bottom layer, as shown in Fig. A1(b). Let us also assume that $\lambda_1 < \lambda_2$, because a low thermal conductivity channel is placed on top of a high thermal conductivity substrate for high-performance power electronics devices [11]. To extend Eq. (A1) to a bilayer substrate, we consider a constant spreading angle α for both layers and rewrite Eq. (A1) as:

Fig. A1. (a) Schematic of a bulk substrate, with a spreading angle, ω and thermal conductivity, λ . (b) Schematic of a bilayer substrate, with a spreading angle, ω_1 and ω_2 , thermal conductivity, λ_1 and λ_2 , and widths ℓ_1 and ℓ_2 , for the top and bottom layers, respectively. (c) COMSOL simulation to obtain θ_{th} of a bilayer structure. Here, Fourier Equation, $q = -\kappa \nabla T$, has been solved. Power of 1W has been applied of the structure and $\theta_{th} = \Delta T/P$ (d) Comparison of Eq. (A2), with 3D COMSOL simulation.

$$\theta_{th, \text{bilayer}} = \frac{1}{\lambda_1 \pi a} \frac{\ell_1 + (\ell_2 \times \lambda_1 / \lambda_2)}{(a + (\ell_1 + \ell_2) \tan \omega)} \quad (A2)$$

Eq.(A2) provides a reasonable approximation of θ_{th} as confirmed by 3D COMSOL simulations, shown in Fig A1(d). Even though the range of λ_2 is much larger than λ_1 , θ_{th} is accurately reproduced using Eq. (A2). It is to be noted that Eq. (A2) should only be used for back-of-the-hand approximations of θ_{th} and not as a replacement of bilayer θ_{th} determining closed-form formulas, numerical expressions, or TCAD.

B. 3D Thermal Resistance Model

A more sophisticated analytical model, originally developed by Darwish et al. [61], considers devices with much wider gate width compared to gate length ($W_g \gg L_g$). There are three components of the thermal resistance (labeled in subscripts I, II, and III, with $\theta_{th, \text{tot}} = \theta_{th,I} + \theta_{th,II} + \theta_{th,III}$), for the active layer, and upper/lower part of the substrate. Due to the prolonged gate width (hence the heat source), instead of a spherical heat spreading, a spheroid spreading is expected. With reasonable accuracy, we simplify the original thermal resistance model in [61] as follows:

$$\theta_{th,I} = \frac{1}{\pi W_g \lambda_{ch}} \ln \left(\frac{4D_{ch}}{\pi L_g} \right). \quad (A3)$$

$$\theta_{th,II} = \frac{1}{\pi W_g \lambda_{sub}} \ln \left(\frac{r_A^{II} - 1}{r_B^{II} - 1} \right). \quad (A4)$$

$$\theta_{th,III} = \frac{1}{2\pi s \lambda_{sub}} \ln \left(\frac{r_B^{III} + 1}{r_B^{III} - 1} \right). \quad (A5)$$

where $r_A^{II} = \frac{\pi^2 W_g \lambda_{sub}}{8D_{ch} \lambda_{ch}}$, $r_B^{II} = \sqrt{\left(\frac{W_g}{2}\right)^2 - \left(\frac{4\lambda_{ch} D_{ch}}{\pi^2 \lambda_{sub}}\right) + \left(\frac{s}{\sqrt{2}}\right)^2} / \frac{s}{\sqrt{2}}$ and $r_B^{III} = \sqrt{\left(\frac{W_g}{2}\right)^2 + \left(\frac{\pi D_{sub}}{2}\right)^2} / \frac{\pi D_{sub}}{2}$ and s is the length for adiabatic boundary conditions.

C. Transient Thermal Response of a Packaged chip

It is extremely important to calculate the transient thermal response of the chip accurately to determine the *i*-SOA. The junction temperature can be approximated by the superposition of the heating and cooling responses of the chip. For a train of repetitive pulses, the power pulses can be averaged, and the temperature calculated at the end of n th or $(n+1)$ th pulse after the average power pulse. The expression is given by [62]:

$$Z_1 = D + (1 - D)Z_0(DT) \quad (A6)$$

where D is the duty cycle, Z_0 is the transient thermal impedance measured experimentally. For a single pulse, $Z_0(t_{on}) = 1 - \exp(-t_{on}/\tau_{th})$, with $\tau_{th} (\equiv \theta_{th} C_{th})$ and T is the period. Another approach is to calculate the temperature at the end of the average power pulse (before steady-state conditions), where the average power is modified by a transient thermal resistance factor, given as [62]:

$$Z_2 = D + (1 - D)Z_0(D + 1)T + Z_0(DT) - Z_0(T) \quad (A7)$$

While both A6 and A7 provide a reasonable estimation of transient thermal response, they were derived using the superposition principle, since it defies a solution otherwise. Here, we will derive a closed-form analytical relation to obtain the transient thermal response of a packaged chip, and compare it with those obtained using the superposition principle. We know from [17] that, $T_{j,max}^{pk} - T_{amb} = \Delta T_L^{pk}$ and $P^{pk} = P_{max}$. Also,

$$\Delta T_L^{pk} = P_{avg}\theta_{th} + H(P^{pk} - P_{avg}) = P^{pk}R\theta_{th}[D + (1 - D)H_0]. \quad (A8)$$

Therefore, we can write:

$$Z = \frac{\Delta T_L^{pk}}{\theta_{th}P_{max}} = \frac{\Delta T_L^{pk}}{\theta_{th}P^{pk}} = D + (1 - D)H_0. \quad (A9)$$

where $H_0 = \left(1 - e^{\left(-\frac{D\zeta}{\tau_{th}}\right)}\right)\left(1 - e^{\left(-\frac{(1-D)\zeta}{\tau_{th}}\right)}\right)/(1 - e^{\left(-\frac{\zeta}{\tau_{th}}\right)}) = CZ_0$.

For a single-time-constant system, H_0 in [52] is exact, therefore missing the infinite series contribution, i.e.,

$$C = H_0/Z_0(t) = 1 - e^{\left(-\frac{(1-D)\zeta}{\tau_{th}}\right)}/1 - e^{\left(-\frac{\zeta}{\tau_{th}}\right)}. \quad (A10)$$

From [18], for a packaged device, if $\tau_{th,1} \ll \tau_{th,2} \ll \dots \tau_{th,n}$, ΔT of successive stages can be added, so that $\Delta T(t) = \sum_i \Delta T_i \left(1 - \exp\left(-\frac{t}{\tau_{th,i}}\right)\right)$. Now dividing both sides with the dissipated power, P_D , we get:

$$\frac{\Delta T(t)}{P_D} = \sum_i \frac{\Delta T_i}{P_D} Z_{0,i}(t) \Rightarrow Z_0(t) = \sum_i \frac{\theta_{th,i}}{\theta_{th,tot}} Z_{0,i}(t). \quad (A11)$$

Fig. A2. Comparison of expressions for transient thermal responses of a packaged chip derived using superposition principle (Z_1 (Eq. (A6)) and Z_2 (Eq. (A7))) and the closed form analytical solution derived in this paper (Z_m (Eq. (A12))). For the comparison, the thermal time constant, τ was taken as 0.0005, which is a typical value for microchips. Although the curves are obtained for three values of duty cycles ($D = 0.1, 0.3$ and 0.6), matching of Z_3 with Z_1 and Z_2 has been confirmed at other values of duty cycles and thermal time constants as well.

where $Z_0(t)$ is the average of all individual stage $Z_{0,i}(t)$, and $\theta_{th,tot}$ is the summation of all θ_{th} of the packaged chip.

Therefore, a multi-stage transient thermal resistance (Eq. (A11)) including the correction factor $C(D, \zeta)$ (Eq. (A10)) and duty cycle D (Eq. (A9)) can be expressed as:

$$Z_m(t) = D + (1 - D) \sum_i \frac{\theta_{th,i}}{\theta_{th,tot}} C_i(D, \zeta) Z_{0,i}(t). \quad (A12)$$

Fig. A2 shows the derived analytical closed-form solution of transient thermal response, Z_m (Eq. (A12)) matches the responses predicted by Z_1 (Eq. A(6)) and Z_2 (Eq. A(7)) very well.

D. Device Geometry and Parameters Used for Calculations.

Table T1: Device Dimensions used in calculations.

Material	Si	SiC	GaN	β -Ga ₂ O ₃	Diamond
Bandgap (eV)	1.1	3.25	3.4	4.85	5.47
Dielectric Const.	11.8	9.7	9	10	5.5
Thermal Cond. (W/cmK)	1.5	4.9	2.3	0.2	20
Electron Mobility (cm ² /Vs)	1480	1000	1250	300	2000
Breakdown Field (MV/cm)	0.3	2.5	3.3	8	10
Sp. Heat (J/K-g)	0.7	0.69	0.49	0.49	0.52
Density (g/cm ³)	2.33	3.1	6.15	5.95	3.52
$C_{th}/W(J/K-cm) (\times 10^{-5})$	4.89	642	904	875	549

Table T2: Device Parameters used in calculations.

	Layers	Length	Width	Thickness
Bulk Substrate	Bulk	4 μ m	50 μ m	300 μ m
Bilayer Structure	Layer 1	4 μ m	50 μ m	5 μ m
	Layer 2	4 μ m	50 μ m	300 μ m

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