TCAD Parameters for 4H-SiC: A Review

Jürgen Burin,[1] Philipp Gaggl,[1] Simon Waid,[1] Andreas Gsponer,[1] and Thomas Bergauer[1]
Institute of High Energy Physics, Austrian Academy of Sciences, Nikolsdorfer Gasse 18, 1050 Wien

(*e-mail: juergen.burin@oeaw.ac.at)

(Dated: 27 September 2024)

In this paper we review the models and their parameters to describe the relative permittivity, bandgap, impact ionization, mobility, charge carrier recombination/effective masses and incomplete dopand ionization of 4H silicon carbide in computer simulations. We aim to lower the entrance barrier for newcomers and provide a critical evaluation of the status quo to identify shortcomings and guide future research. The review reveals a rich set of often diverging values in literature based on a variety of calculation and measurement methods. Although research for all the selected parameters is still active, we show that sometimes old values or those determined for other kinds of silicon carbide are commonly used.

Keywords: 4H-SiC, TCAD simulations, simulation parameters, silicon carbide

I. RELATIVE PERMITTIVITY

The permittivity ε describes the dielectric properties that influence electromagnetic wave propagation within a material and their reflections on interfaces[1]. These effects are, for example, essential to describe the impact of an external electric field, which determines the capacitance values in a device. In general, the user has to provide the relative permittivity $\varepsilon_\mathrm{r} = \varepsilon/\varepsilon_0$, i.e., the ratio compared to the vacuum permittivity $\varepsilon_0 = 8.854 \times 10^{-12}\,\mathrm{F\,m^{-1}}$, to the TCAD tools.

A. Theory

In the frequency domain, the complex relative permittivity can be written as

$$\varepsilon_\mathrm{r}^*(\omega) = \varepsilon'(\omega) + \mathrm{i}\varepsilon''(\omega).$$

The real part ε' represents the energy stored in the material when exposed to an electric field and the imaginary part ε'' the losses (e.g., absorption and attenuation)[1]. ε' and ε'' are tightly interconnected via the Kramers-Kronig (KK) relation[2]

$$\varepsilon'(\omega) = 1 + \frac{2}{\pi}\int_0^\infty \frac{\omega'\varepsilon''(\omega')}{\omega'^2 - \omega^2}\mathrm{d}\omega' \tag{1a}$$

$$\varepsilon''(\omega) = -\frac{2\omega}{\pi}\int_0^\infty \frac{\varepsilon'(\omega')}{\omega'^2 - \omega^2}\mathrm{d}\omega' \tag{1b}$$

In TCAD simulations of semiconductor devices ε'' is of diminishing importance, but ε' is required to calculate capacitances or the electric field distribution. Consequently, we will focus on ε' in the sequel.

In the literature the static (ε_s) and high-frequency resp. optical (ε_∞) relative permittivity are distinguished. The former is $\varepsilon'(\omega \to 0)$ but a definition of the latter is more complicated. It denotes ε' at the end of the reststrahlen range towards higher frequencies, where the real part of the refractive index is null[3]. In publications that focus on optical high-frequency analysis ε_∞ is sometimes denoted as $\varepsilon'(0)$[4], which must not be confused with ε_s. These inconsistencies were explained in the following fashion[5]: “We shall use ε_∞ to denote the extrapolation … to zero frequency. This somewhat contradictory notation arose because ε_∞ the "optical" dielectric constant, was often set … at a frequency much higher than the lattice frequency, but low compared with electronic transition frequencies. In many substances no suitable frequency exists, and it is preferable to extrapolate optical data to zero frequency …”

To clarify: ε_∞ is measured at frequencies well above the long-wavelength longitudinal optical (LO) phonon frequency ω_{LO}[2]. ω_{LO} translates ε_{s} into ε_∞ and vice versa in conjunction with the transversal optical (TO) phonon frequency ω_{TO} and the Lyddane-Sachs-Teller (LST) relationship[6]

$$\frac{\varepsilon_{\mathrm{s}}}{\varepsilon_\infty} = \left(\frac{\omega_{LO}}{\omega_{TO}}\right)^2 . \tag{2}$$

For ω_{LO} we encountered the energy values 120 meV (approximately 29 THz)[7–11], 104 to 121 meV[12] and 104.2 meV[13] in our search. Instead of the energy often the respective wave numbers are presented, i.e., (in cm^{-1}) $\omega_{\mathrm{TO}} = 793$ and $\omega_{\mathrm{LO}} = 974$[14], $\omega_{\mathrm{LO}}^{\parallel} = 964.2, \omega_{\mathrm{LO}}^{\perp} = 966.4, \omega_{\mathrm{TO}}^{\parallel} = 783$ and $\omega_{\mathrm{TO}}^{\perp} = 798$[15], $\omega_{\mathrm{TO}} = 783$ and $\omega_{\mathrm{LO}} = 964$[16] and $\omega_{\mathrm{LO}} \in [967, 971]$[17].

B. Results

Various approaches have been used to determine the relative permittivity: One possibility are calculations using the density functional theory (DFT) based local density approximation (LDA)[4,7,18–23] or the effective mass theory[24]. With these the band structure and, thus, ε'' is calculated and then transformed into ε' using the Kramers-Kronig relations (Eq. (1)). Measurements use either some form of resonator (RES)[25–27], spectroscopy (SPEC)[28–30], spectroscopic ellipsometry (SE)[31,32] or the refractive index (RI)[5,15,33]. In some cases he transversal and longitudinal optical phonon frequencies is determined and used in the LST relationship (Eq. (2))[31,32]. Furthermore, the tight relationship between relative permittivity and complex refractive index, i.e., $n^*(E) = \sqrt{\varepsilon(E)}$[2], with $E = \hbar\omega$, is utilized if ε'' is negligible. For fitting purposes the representation

$$n^2 = 1 + \frac{\varepsilon_g}{1 - (hf/E_{\mathrm{g}})^2} \approx \varepsilon_\infty + \varepsilon_{\mathrm{g}} \left(\frac{hf}{E_{\mathrm{g}}}\right) ,$$

with hf the photon energy, E_{g} an "average band gap" and ε_{g} proportional to the oscillator strength[5], is used to extract ε_∞[5,15,29,33]. Finally, fitting to $\ln(J/E)$[34], with J the current density, is also deployed.

The relative permittivity was furthermore investigated at mm-wave frequencies (MM) (10 GHz to 10 THz)[26,35–38] (nicely summarized by Li *et al.* [27], Yanagimoto *et al.* [39]). Unfortunately, there are often fluctuations in the data or just single data points available, which makes an interpolation to zero frequency ($= \varepsilon_{\mathrm{s}}$) not possible. For these reasons we had to discard most of the respective data. We also excluded publications whose values got refined in succeeding experiments[40,41], that

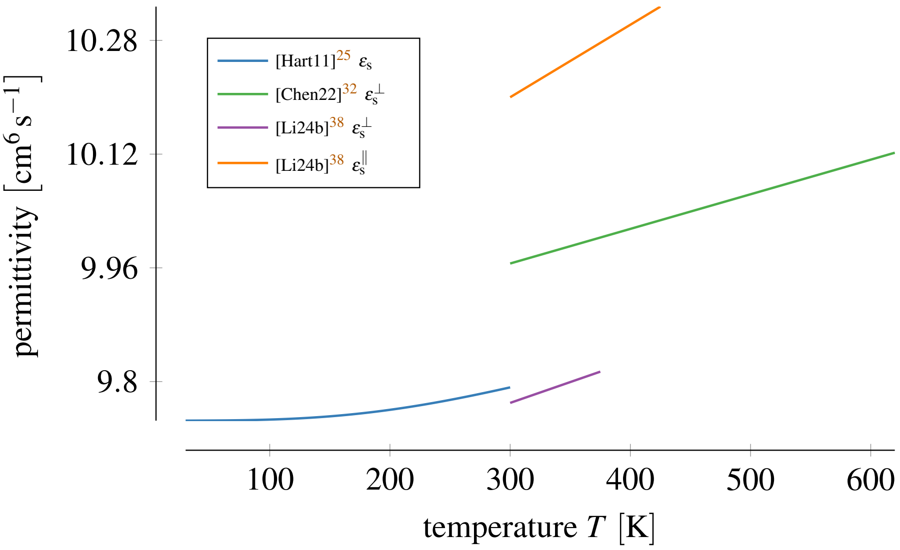

FIG. 1. Temperature dependency of the permittivity.

did not specify the investigated polytype[42–45] or where an extraction of the data values was not possible[46].

With the listed characterization approaches values in the range of $[9.6, 10.65]$ for the static relative permittivity and $[6.25, 7.61]$ for the high-frequency one have been achieved (Table I). In the table we also show two references that exclusively provide 6H values because these are often referenced for 4H investigations. Wherever necessary we calculated the relative permittivity according to $\varepsilon_\mathrm{s} = (\varepsilon_\mathrm{s}^{\|}\varepsilon_\mathrm{s}^{\perp 2})^{\frac{1}{3}}$ resp. $\varepsilon_\infty = (\varepsilon_\infty^{\|}\varepsilon_\infty^{\perp 2})^{\frac{1}{3}}$[47–51], which far more often used than $\varepsilon_\mathrm{s} = (\varepsilon_\mathrm{s}^{\|}\varepsilon_\mathrm{s}^{\perp})^{\frac{1}{2}}$ proposed by Ivanov *et al.* [24].

In TCAD tools the permittivity is a constant although research showed that there is a frequency[25] and temperature[25,32] dependency. For a frequency around 40 GHz Hartnett *et al.* [25] provided the approximation

$$\varepsilon_\mathrm{s}(T) = 9.7445 + 3.1862\times10^{-5}\,T - 6.3026\times10^{-7}\,T^2 + 5.9848\times10^{-9}\,T^3 - 8.2821\times10^{-12}\,T^4 \;,$$

with the temperature T in K. Cheng, Yang, and Zheng [32] approximated $\varepsilon_\mathrm{s}^{\perp} = 9.82 + 4.87\times10^{-4}\,T$ and Li *et al.* [38] $\varepsilon_\mathrm{s}^{\perp} = 9.77 * (1 + 6\times10^{-5}(T - 300\,\mathrm{K})$ and $\varepsilon_\mathrm{s}^{\|} = 10.2 * (1 + 1\times10^{-4}(T - 300\,\mathrm{K})$. All approximations show an increase of the permittivity with temperature (Fig. 1).

TABLE I. Published relative permittivity values.

ref.	ε_s	$\varepsilon_s^{\parallel}$	$\varepsilon_s^{\perp}$	ε_∞	$\varepsilon_\infty^{\parallel}$	$\varepsilon_\infty^{\perp}$	method[a]	SiC	doping
[Patr70][5]	9.78[c]	10.03	9.66	6.58[c]	6.7	6.52	RI	6H	-
[Iked80][33]	9.94[c]	10.32	9.76	-	-	-	RI	4H	-
[Nino94][31]	9.83[c]	9.98	9.76	6.62[c]	6.67	6.59	SE	6H	-
[Hari95][15]	-	-	-	6.63[c]	6.78	6.56	RI	4H	-
[Karc96][18]	10.53[c]	10.9	10.352	7.02[c]	7.169	6.946	DFT-LDA	4H	-
[Well96][19]	-	-	-	7.02[c]	7.17	6.95	DFT-LDA	4H	-
[Adol97][20]	-	-	-	7.56[c]	7.61	7.54	DFT-LDA	4H	-
[Ahuj02][7]	-	-	-	7.11[c]	7.47	6.94	DFT-LDA	4H	n-type
[Peng04][21]	-	-	-	6.31[c]	6.44	6.25	DFT	4H	-
[Pers05][52]	9.73[c]	9.94	9.63	6.47[c]	6.62	6.4	DFT-LDA	4H	intrinsic
[Chin06][4]	-	-	-	6.81	-	-	DFT-LDA	4H	intrinsic
[Dutt06][35]	9.97 ± 0.02[b]	-	-	-	-	-	MM	4H	high purity
[Ivan06][24]	9.93 ± 0.01	-	-	-	-	-	EMT	4H	intrinsic
[Hart11][25]	9.77[d]	-	-	-	-	-	RES	4H	high purity
[Jone11][26]	9.6	-	-	-	-	-	RES	4H	high purity
[Naft16][28]	10.11[c]	10.53[f]	9.91[f]	-	-	-	SPEC	4H	undoped
[Cout17][23]	10.13[c]	10.65	9.88	-	-	-	DFT-LDA	4H	-
[Tare19][29]	-	-	-	6.587 ± 0.003	-	-	SPEC	4H	-
[Chen22][32]	9.97[g]	-	-	-	-	-	SE	4H	-
[Gao22a][30]	-	-	-	6.51	-	-	SPEC	4H	-
[Yang22a][34]	10.21	-	-	-	-	-	$\ln(J/E)$	4H	p-type
[Li23][27]	-	10.27 ± 0.03	-	-	-	-	RES	4H	high purity
[Li24b][38]	9.91[c]	10.20 ± 0.05	9.77 ± 0.01	-	-	-	RES	4H	high purity

[a] description of the single methods in the text

[b] frequency range 131–145 GHz, for lower resp. higher frequencies $\varepsilon_s = 9.74$ was achieved

[c] $\varepsilon_s = (\varepsilon_s^{\perp 2} \varepsilon_s^{\parallel})^{1/3}$

[d] temperature and frequency dependent

[e] calculated from refractive index n as $\varepsilon_s = n^2$

[f] wavelength-dependent refractive index presented

[g] temperature dependent

C. Discussion

We identified two very influential publications, largely dominating the permittivity values found in literature. Ikeda, Matsunami, and Tanaka[33] published, based on measurements from Shaffer[53], in 1980 the first 4H-SiC permittivity data. Although these values are broadly used in literature[22,54–58], we never found a citation of that particular paper. Not even cross-references among the citing publications exist.

In 1970, so ten years prior to the first 4H values, Patrick and Choyke[5] determined, based on measurements published in 1944[59], the permittivity of the 6H polytype. Many publications on 4H-SiC used these results (see Fig. 2) despite the deviating polytype. Some authors claimed that dedicated 4H values were not available[12,48,60–63], a mistake as we showed before. Nevertheless, it is still claimed up to this day[32]. This shows, how hard it is to get a comprehensive overview over 4H-SiC TCAD parameters. In contrast to early analysis, that clearly highlight that 6H values were used[64], the majority of publications simply adopts the parameters without further remark, which leaves the false impression that proper 4H values were used.

Rounding of the original values, e.g., $9.66 \rightarrow 9.7 \rightarrow 10$[67,78] (see Fig. 2), and mere typographical errors, e.g., turning 9.66 into 9.67[87] (a comprehensive analysis of all encountered inconsistencies is shown in **??**), expanded the range of available values (see Figs. 3 and 4). In these figures we connected those values where at least one direct connection could be found. Due to missing references we can, however, not guarantee that all authors made their selection based on the same data. In many cases, e.g., for the prominent values $\varepsilon_\mathrm{s} = 9.7$ or $\varepsilon_\mathrm{s} = 10$, it is not unreasonable to assume that simply the permittivity in one principal direction was picked.

An interesting case is $\varepsilon_\mathrm{s} = 8.5584$[89,90], which is supposed to be based on $\varepsilon_\mathrm{s}^{\perp} = 9.66$ and $\varepsilon_\mathrm{s}^{\parallel} = 10.03$[88]. We were not able to achieve this value analytically since the result is lower than both consitutents. Only when we added the high-frequency relative permittivity to the calculations we achieved a somewhat close value of 8. Such a combination is, however, not justifiable.

Overall, the missing awareness regarding 4H related permittivity values is striking. One explanation why the same old values are reused over and over again are the often very long citation (see Fig. 2). Combined with often missing references this makes it difficult to pinpoint the origin of a value and thus assess its suitability. Another interpretation of the achieved results is that the permittivity has little impact in TCAD simulations, such that somewhat accurate 6H values are already sufficient. Nevertheless, even if this was the case, we highly encourage the scientific community to adopt the most recent measurement 4H-SiC in future publications to make these values more prominently known and, thus, lead to a wider distribution.

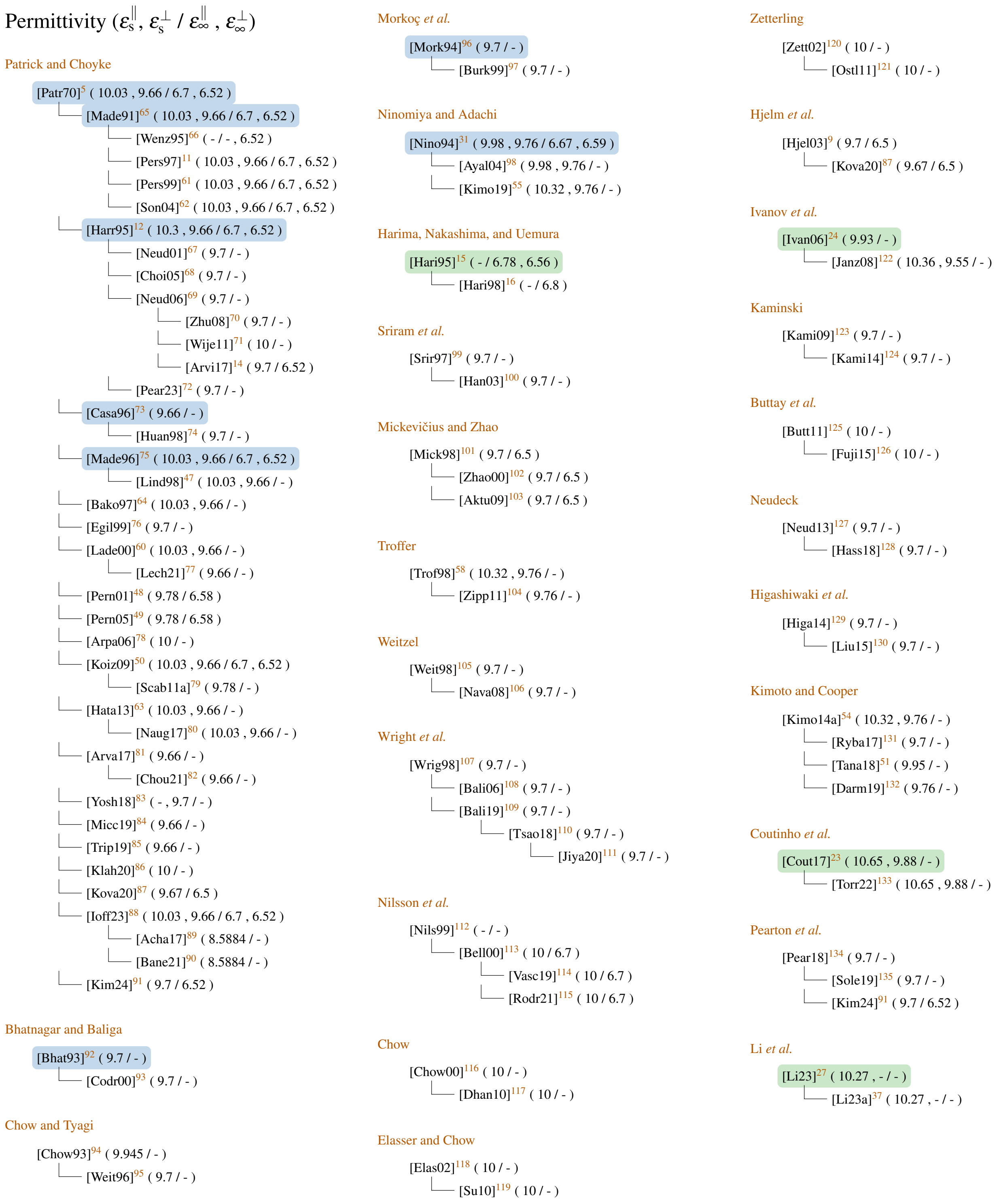

FIG. 2. Reference chains found for the relative permittivity. Publications with blue background are not focused on 4H-SiC, while those in green are novel analyses on 4H-SiC.

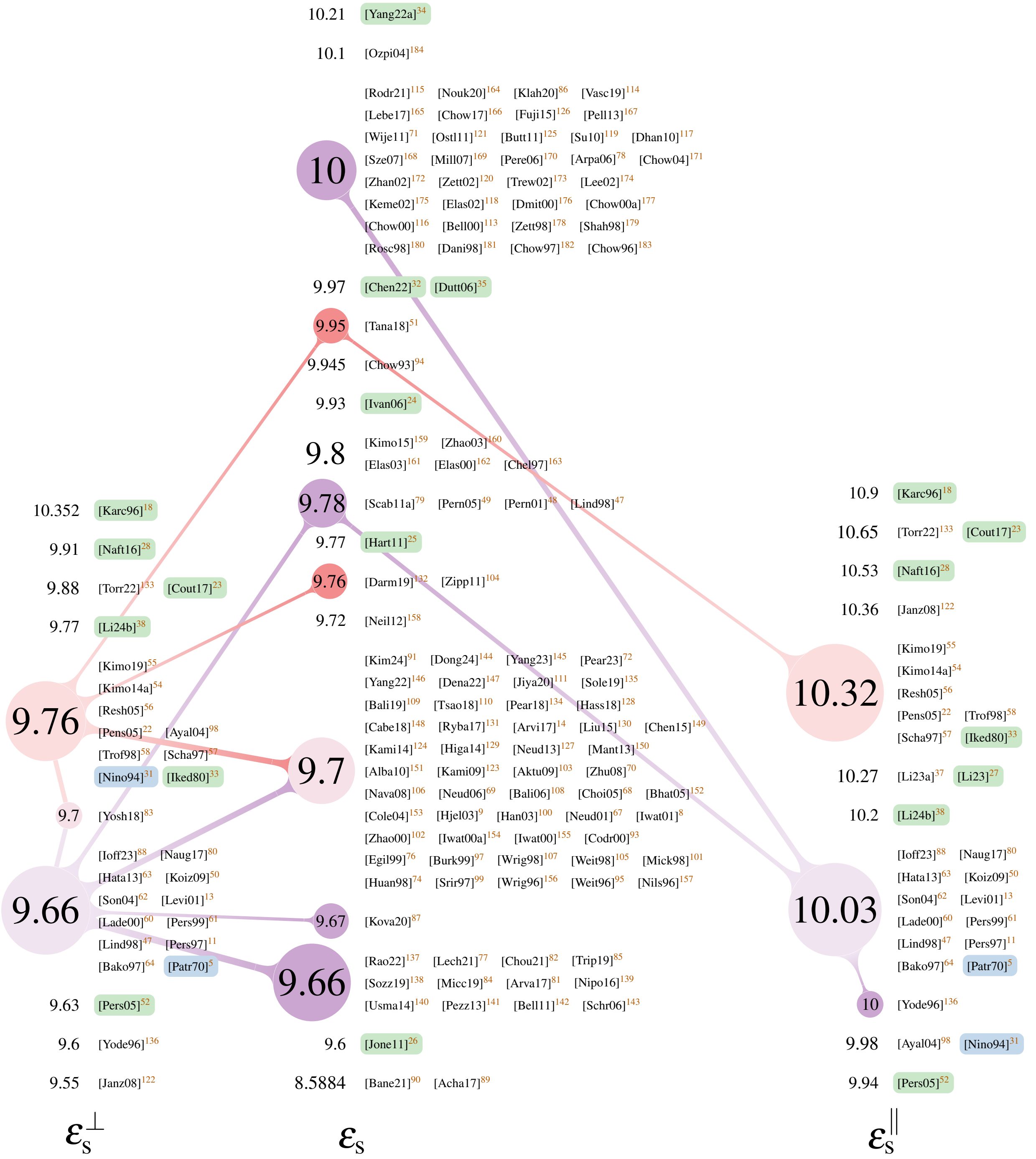

FIG. 3. Published values for the static permittivity. Connected values indicated that at least one connection has been found. References with blue background indicate investigations of non-4H silicon carbide while green background denotes basic 4H-SiC investigations.

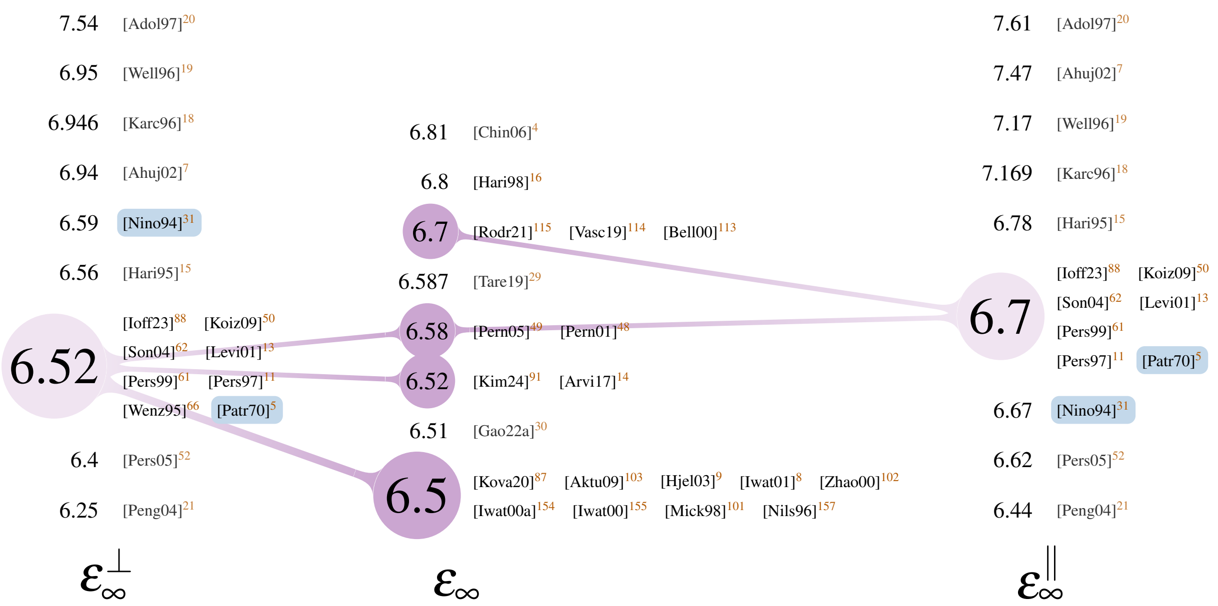

FIG. 4. Published values for the high-frequency permittivity. Connected values indicated that that at least one connection has been found. References with green background indicate investigations of non-4H silicon carbide while blue background denotes basic 4H-SiC investigations.

REFERENCES

[1] V. Komarov, S. Wang, and J. Tang, in *Encyclopedia of RF and Microwave Engineering*, edited by K. Chang (Wiley, 2005) 1st ed.

[2] S. Adachi, *Properties of Group-IV, III-V and II-VI Semiconductors* (John Wiley, Chichester, England, 2005).

[3] J. Olivares, M. DeMiguel-Ramos, E. Iborra, M. Clement, T. Mirea, M. Moreira, and I. Katardjiev, in *2013 Joint European Frequency and Time Forum & International Frequency Control Symposium (EFTF/IFC)* (IEEE, Prague, Czech Republic, 2013) pp. 118–121.

[4] W. Ching, Y.-N. Xu, P. Rulis, and L. Ouyang, Materials Science and Engineering: A **422**, 147 (2006).

[5] L. Patrick and W. J. Choyke, Physical Review B **2**, 2255 (1970).

[6] R. H. Lyddane, R. G. Sachs, and E. Teller, Physical Review **59**, 673 (1941).

[7] R. Ahuja, A. Ferreira Da Silva, C. Persson, J. M. Osorio-Guillén, I. Pepe, K. Järrendahl, O. P. A. Lindquist, N. V. Edwards, Q. Wahab, and B. Johansson, Journal of Applied Physics **91**, 2099 (2002).

[8] H. Iwata and K. M. Itoh, Journal of Applied Physics **89**, 6228 (2001).

[9] M. Hjelm, H.-E. Nilsson, A. Martinez, K. F. Brennan, and E. Bellotti, Journal of Applied Physics **93**, 1099 (2003).

[10] R. Mickevičius and J. H. Zhao, Materials Science Forum **264–268**, 291 (1998).

[11] C. Persson and U. Lindefelt, Journal of Applied Physics **82**, 5496 (1997).

[12] G. L. Harris and Inspec, eds., *Properties of Silicon Carbide*, EMIS Datareviews Series No. 13 (INSPEC, the Inst. of Electrical Engineers, London, 1995).

[13] M. E. Levinshteĭn, S. L. Rumyantsev, and M. Shur, eds., *Properties of Advanced Semiconductor Materials: GaN, AlN, InN, BN, SiC, SiGe* (Wiley, New York, 2001).

[14] I.-R. Arvinte, *Investigation of Dopant Incorporation in Silicon Carbide Epilayers Grown by Chemical Vapor Deposition*, Ph.D. thesis, Universite Cote d'Azur (2017).

[15] H. Harima, S.-i. Nakashima, and T. Uemura, Journal of Applied Physics **78**, 1996 (1995).

[16] H. Harima, T. Hosoda, and S. Nakashima, Materials Science Forum **264–268**, 449 (1998).

[17] D. W. Feldman, J. H. Parker, W. J. Choyke, and L. Patrick, Physical Review **173**, 787 (1968).

[18] K. Karch, F. Bechstedt, P. Pavone, and D. Strauch, Physical Review B **53**, 13400 (1996).

[19] G. Wellenhofer, K. Karch, P. Pavone, U. Rössler, and D. Strauch, Physical Review B **53**, 6071 (1996).

[20] B. Adolph, K. Tenelsen, V. I. Gavrilenko, and F. Bechstedt, Physical Review B **55**, 1422 (1997).

[21] X. Peng-Shou, X. Chang-Kun, P. Hai-Bin, and X. Fa-Qiang, Chinese Physics **13**, 2126 (2004).

[22] G. Pensl, F. Ciobanu, T. Frank, M. Krieger, S. Reshanov, F. Schmid, and M. Weidner, International Journal of High Speed Electronics and Systems **15**, 705 (2005).

[23] J. Coutinho, V. J. B. Torres, K. Demmouche, and S. Öberg, Physical Review B **96**, 174105 (2017).

[24] I. G. Ivanov, A. Stelmach, M. Kleverman, and E. Janzén, Physical Review B **73**, 045205 (2006).

[25] J. G. Hartnett, D. Mouneyrac, J. Krupka, J.-M. Le Floch, M. E. Tobar, and D. Cros, Journal of Applied Physics **109**, 064107 (2011).

[26] C. R. Jones, J. Dutta, G. Yu, and Y. Gao, Journal of Infrared, Millimeter, and Terahertz Waves **32**, 838 (2011).

[27] L. Li, S. Reyes, M. J. Asadi, X. Wang, G. Fabi, E. Ozdemir, W. Wu, P. Fay, and J. C. M. Hwang, in *2023 100th ARFTG Microwave Measurement Conference (ARFTG)* (IEEE, Las Vegas, NV, USA, 2023) pp. 1–4.

[28] M. Naftaly, J. F. Molloy, B. Magnusson, Y. M. Andreev, and G. V. Lanskii, Optics Express **24**,

2590 (2016).

[29] A. T. Tarekegne, B. Zhou, K. Kaltenecker, K. Iwaszczuk, S. Clark, and P. U. Jepsen, Optics Express **27**, 3618 (2019).

[30] M.-m. Gao, L.-y. Fan, X.-y. Gong, J.-l. You, and Z.-z. Chen, Journal of Applied Physics **132**, 135702 (2022).

[31] S. Ninomiya and S. Adachi, Japanese Journal of Applied Physics **33**, 2479 (1994).

[32] L. Cheng, J.-Y. Yang, and W. Zheng, ACS Applied Electronic Materials **4**, 4140 (2022).

[33] M. Ikeda, H. Matsunami, and T. Tanaka, Physical Review B **22**, 2842 (1980).

[34] Q. Yang, Q. Liu, W. Xu, D. Zhou, F. Ren, R. Zhang, Y. Zheng, and H. Lu, Solid-State Electronics **187**, 108196 (2022).

[35] J. M. Dutta, G. Yu, and C. R. Jones, in *2006 Joint 31st International Conference on Infrared Millimeter Waves and 14th International Conference on Teraherz Electronics* (IEEE, Shanghai, China, 2006) pp. 411–411.

[36] S. Chen, M. Afsar, and D. Sakdatorn, IEEE Transactions on Instrumentation and Measurement **57**, 706 (2008).

[37] L. Li, S. Reyes, M. J. Asadi, P. Fay, and J. C. M. Hwang, Applied Physics Letters **123**, 012105 (2023).

[38] T. Li, L. Li, X. Wang, J. C. M. Hwang, S. Yanagimoto, and Y. Yanagimoto, IEEE Journal of Microwaves , 1 (2024).

[39] Y. Yanagimoto, S. Yanagimoto, T. Li, and J. C. M. Hwang, in *2024 103rd ARFTG Microwave Measurement Conference (ARFTG)* (IEEE, Washington, DC, USA, 2024) pp. 1–4.

[40] I. G. Ivanov, B. Magnusson, and E. Janzén, Physical Review B **67**, 165211 (2003).

[41] I. G. Ivanov, B. Magnusson, and E. Janzén, Physical Review B **67**, 165212 (2003).

[42] A. Agarwal, S.-H. Ryu, and J. Palmour, in *Silicon Carbide*, edited by W. J. Choyke, H. Matsunami, and G. Pensl (Springer Berlin Heidelberg, Berlin, Heidelberg, 2004) pp. 785–811.

[43] D. Hofman, J. Lely, and J. Volger, Physica **23**, 236 (1957).

[44] A. Schöner, in *Silicon Carbide*, edited by W. J. Choyke, H. Matsunami, and G. Pensl (Springer Berlin Heidelberg, Berlin, Heidelberg, 2004) pp. 229–250.

[45] I. Polaert, N. Benamara, J. Tao, T.-H. Vuong, M. Ferrato, and L. Estel, Chemical Engineering and Processing: Process Intensification **122**, 339 (2017).

[46] J. Chen, Z. H. Levine, and J. W. Wilkins, Physical Review B **50**, 11514 (1994).

[47] U. Lindefelt, Journal of Applied Physics **84**, 2628 (1998).

[48] J. Pernot, W. Zawadzki, S. Contreras, J. L. Robert, E. Neyret, and L. Di Cioccio, Journal of Applied Physics **90**, 1869 (2001).

[49] J. Pernot, S. Contreras, and J. Camassel, Journal of Applied Physics **98**, 023706 (2005).

[50] A. Koizumi, J. Suda, and T. Kimoto, Journal of Applied Physics **106**, 013716 (2009).

[51] H. Tanaka, S. Asada, T. Kimoto, and J. Suda, Journal of Applied Physics **123**, 245704 (2018).

[52] C. Persson and A. Ferreira Da Silva, in *Optoelectronic Devices: III Nitrides* (Elsevier, 2005) pp. 479–559.

[53] P. T. B. Shaffer, Applied Optics **10**, 1034 (1971).

[54] T. Kimoto and J. A. Cooper, *Fundamentals of Silicon Carbide Technology: Growth, Characterization, Devices, and Applications*, 1st ed. (Wiley, 2014).

[55] T. Kimoto, in *Wide Bandgap Semiconductor Power Devices* (Elsevier, 2019) pp. 21–42.

[56] S. Reshanov, *Device-Relevant Defect Centers and Minority Carrier Lifetime in 3C-, 4H- and 6H-SiC*, Ph.D. thesis, Erlangen-Nürnberg, Germany (2005).

[57] M. Schadt, *Transporteigenschaften von Elektronen Und Löchern in Siliciumkarbid*, Ph.D. thesis, FriedrichAlexander-Universität (1997).

[58] T. Troffer, *Elektrische Und Optische Charakterisierung Bauelementrelevanter Dotierstoffe in Siliciumkarbid*, Ph.D. thesis, FriedrichAlexander-Universität (1998).

[59] N. W. Thibault, American Mineralogist **29**, 327 (1944), https://pubs.geoscienceworld.org/msa/ammin/article-pdf/29/9-10/327/4243453/am-1944-327.pdf.

[60] M. Lades, *Modeling and Simulation of Wide Bandgap Semiconductor Devices: 4H/6H-SiC*, Ph.D. thesis, Technische Universität München (2000).

[61] C. Persson, U. Lindefelt, and B. E. Sernelius, Journal of Applied Physics **86**, 4419 (1999).

[62] N. T. Son, C. Persson, U. Lindefelt, W. M. Chen, B. K. Meyer, D. M. Hofmann, and E. Janzén, in *Silicon Carbide*, edited by W. J. Choyke, H. Matsunami, and G. Pensl (Springer Berlin Heidelberg, Berlin, Heidelberg, 2004) pp. 437–460.

[63] T. Hatakeyama, K. Fukuda, and H. Okumura, IEEE Transactions on Electron Devices **60**, 613 (2013).

[64] M. Bakowski, U. Gustafsson, and U. Lindefelt, physica status solidi (a) **162**, 421 (1997).

[65] O. Madelung and R. Poerschke, eds., *Semiconductors: Group IV Elements and III-V Compounds*, Data in Science and Technology (Springer Berlin Heidelberg, Berlin, Heidelberg, 1991).

[66] B. Wenzien, P. Käckell, F. Bechstedt, and G. Cappellini, Physical Review B **52**, 10897 (1995).

[67] P. Neudeck, in *Encyclopedia of Materials: Science and Technology* (Elsevier, 2001) pp. 8508–8519.

[68] Y. Choi, H.-Y. Cha, L. Eastman, and M. Spencer, IEEE Transactions on Electron Devices **52**, 1940 (2005).

[69] P. G. Neudeck (2006).

[70] X. Zhu, *ALTERNATIVE GROWTH AND INTERFACE PASSIVATION TECHNIQUES FOR SiO2 ON 4H-SiC*, Ph.D. thesis, Auburn University (2008).

[71] M. B. Wijesundara and R. Azevedo, *Silicon Carbide Microsystems for Harsh Environments*, MEMS Reference Shelf, Vol. 22 (Springer New York, New York, NY, 2011).

[72] S. J. Pearton, X. Xia, F. Ren, M. A. J. Rasel, S. Stepanoff, N. Al-Mamun, A. Haque, and D. E. Wolfe, Journal of Vacuum Science & Technology B **41**, 030802 (2023).

[73] J. Casady and R. Johnson, Solid-State Electronics **39**, 1409 (1996).

[74] M. Huang, N. Goldsman, C.-H. Chang, I. Mayergoyz, J. M. McGarrity, and D. Woolard, Journal of Applied Physics **84**, 2065 (1998).

[75] O. Madelung, ed., *Semiconductors — Basic Data* (Springer Berlin Heidelberg, Berlin, Heidelberg, 1996).

[76] T. Egilsson, J. P. Bergman, I. G. Ivanov, A. Henry, and E. Janzén, Physical Review B **59**, 1956 (1999).

[77] B. Lechner, *Behaviour of 4H-SiC Power Semiconductor Devices under Extreme Operating Conditions*, Ph.D. thesis, Technische Universität München (2021).

[78] N. Arpatzanis, A. Tsormpatzoglou, C. A. Dimitriadis, K. Zekentes, N. Camara, and M. Godlewski, physica status solidi (a) **203**, 2551 (2006).

[79] R. . Scaburri, (2011), 10.6092/UNIBO/AMSDOTTORATO/3924.

[80] A. Naugarhiya, P. Wakhradkar, P. N. Kondekar, G. C. Patil, and R. M. Patrikar, Journal of Computational Electronics **16**, 190 (2017).

[81] A. Arvanitopoulos, N. Lophitis, S. Perkins, K. N. Gyftakis, M. Belanche Guadas, and M. Antoniou, in *2017 IEEE 11th International Symposium on Diagnostics for Electrical Machines, Power Electronics and Drives (SDEMPED)* (IEEE, Tinos, Greece, 2017) pp. 565–571.

[82] R. Choudhary, M. Mehta, R. Singh Shekhawat, S. Singh, and D. Singh, Materials Today: Proceedings **46**, 5889 (2021).

[83] H. Yoshioka and K. Hirata, AIP Advances **8**, 045217 (2018).

[84] C. Miccoli and F. Iucolano, Materials Science in Semiconductor Processing **97**, 40 (2019).

[85] S. Tripathi, C. Upadhyay, C. Nagaraj, A. Venkatesan, and K. Devan, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **916**, 246 (2019).

[86] W. M. Klahold, W. J. Choyke, and R. P. Devaty, Physical Review B **102**, 205203 (2020).

[87] A. Kovalchuk, J. Wozny, Z. Lisik, J. Podgorski, L. Ruta, A. Kubiak, and A. Boiadzhian, Journal of Physics: Conference Series **1534**, 012006 (2020).

[88] I. Institute, "Silicon Carbide," http://www.ioffe.ru/SVA/NSM/Semicond/SiC/index.html.

[89] A. Acharyya, Applied Physics A **123**, 629 (2017).

[90] S. Banerjee, in *Advances in Terahertz Technology and Its Applications*, edited by S. Das, N. Anveshkumar, J. Dutta, and A. Biswas (Springer Singapore, Singapore, 2021) pp. 153–172.

[91] H. Kim, Transactions on Electrical and Electronic Materials **25**, 141 (2024).

[92] M. Bhatnagar and B. Baliga, IEEE Transactions on Electron Devices **40**, 645 (1993).

[93] C. Codreanu, M. Avram, E. Carbunescu, and E. Iliescu, Materials Science in Semiconductor Processing **3**, 137 (2000).

[94] T. Chow and R. Tyagi, in *[1993] Proceedings of the 5th International Symposium on Power Semiconductor Devices and ICs* (IEEE, Monterey, CA, USA, 1993) pp. 84–88.

[95] C. Weitzel, J. Palmour, C. Carter, K. Moore, K. Nordquist, S. Allen, C. Thero, and M. Bhatnagar, IEEE Transactions on Electron Devices **43**, 1732 (Oct./1996).

[96] H. Morkoç, S. Strite, G. B. Gao, M. E. Lin, B. Sverdlov, and M. Burns, Journal of Applied Physics **76**, 1363 (1994).

[97] A. Burk, M. O'Loughlin, R. Siergiej, A. Agarwal, S. Sriram, R. Clarke, M. MacMillan, V. Balakrishna, and C. Brandt, Solid-State Electronics **43**, 1459 (1999).

[98] T. Ayalew, *SiC Semiconductor Devices Technology, Modeling, and Simulation*, Ph.D. thesis, TU Wien (2004).

[99] S. Sriram, R. R. Siergiej, R. C. Clarke, A. K. Agarwal, and C. D. Brandt, physica status solidi (a) **162**, 441 (1997).

[100] R. Han, X. Xu, X. Hu, N. Yu, J. Wang, Y. Tian, and W. Huang, Optical Materials **23**, 415 (2003).

[101] R. Mickevičius and J. H. Zhao, Journal of Applied Physics **83**, 3161 (1998).

[102] J. H. Zhao, V. Gruzinskis, Y. Luo, M. Weiner, M. Pan, P. Shiktorov, and E. Starikov, Semiconductor Science and Technology **15**, 1093 (2000).

[103] A. Akturk, N. Goldsman, S. Potbhare, and A. Lelis, Journal of Applied Physics **105**, 033703 (2009).

[104] B. Zippelius, *Elektrische Charakterisierung Bauelement-relevanter Defekte in 3C- Und 4H-Siliziumkarbid*, Ph.D. thesis, Friedrich-Alexander-Universität Erlangen-Nürnberg (2011).

[105] C. Weitzel, Materials Science Forum **264–268**, 907 (1998).

[106] F. Nava, G. Bertuccio, A. Cavallini, and E. Vittone, Measurement Science and Technology **19**, 102001 (2008).

[107] N. G. Wright, D. Morrison, C. M. Johnson, and A. G. O'Neill, Materials Science Forum **264–268**, 917 (1998).

[108] B. J. Baliga, *Silicon Carbide Power Devices* (WORLD SCIENTIFIC, 2006).

[109] B. J. Baliga, *Fundamentals of Power Semiconductor Devices* (Springer International Publishing, Cham, 2019).

[110] J. Y. Tsao, S. Chowdhury, M. A. Hollis, D. Jena, N. M. Johnson, K. A. Jones, R. J. Kaplar, S. Rajan, C. G. Van De Walle, E. Bellotti, C. L. Chua, R. Collazo, M. E. Coltrin, J. A. Cooper, K. R. Evans, S. Graham, T. A. Grotjohn, E. R. Heller, M. Higashiwaki, M. S. Islam, P. W. Juodawlkis, M. A. Khan, A. D. Koehler, J. H. Leach, U. K. Mishra, R. J. Nemanich, R. C. N. Pilawa-Podgurski, J. B. Shealy, Z. Sitar, M. J. Tadjer, A. F. Witulski, M. Wraback, and J. A. Simmons, Advanced Electronic Materials **4**, 1600501 (2018).

[111] I. N. Jiya and R. Gouws, Micromachines **11**, 1116 (2020).

[112] H.-E. Nilsson, E. Bellotti, M. Hjelm, K. F. Brennan, and C. Petersson, **Proceedings of the IMACS Conference, Sofia, Bulgaria, June 1999** (1999).

[113] E. Bellotti, H.-E. Nilsson, K. F. Brennan, P. P. Ruden, and R. Trew, Journal of Applied Physics **87**, 3864 (2000).

[114] J. L. Vasconcelos, C. G. Rodrigues, and R. Luzzi, Materials Science and Engineering: B **249**, 114426 (2019).

[115] C. G. Rodrigues, Semiconductors **55**, 625 (2021).

[116] T. P. Chow, Materials Science Forum **338–342**, 1155 (2000).

[117] G. Dhanaraj, K. Byrappa, V. Prasad, and M. Dudley, eds., *Springer Handbook of Crystal Growth* (Springer Berlin Heidelberg, Berlin, Heidelberg, 2010).

[118] A. Elasser and T. Chow, Proceedings of the IEEE **90**, 969 (2002).

[119] M. Su, (2010), 10.7282/T37944SV.

[120] C.-M. Zetterling, ed., *Process Technology for Silicon Carbide Devices*, EMIS Processing Series

No. 2 (Institution of Electrical Engineers, London, 2002).

[121] M. Östling, Science China Information Sciences **54**, 1087 (2011).

[122] E. Janzén, A. Gali, A. Henry, I. G. Ivanov, B. Magnusson, and N. T. Son, in *Defects in Microelectronic Materials and Devices* (2008) pp. 615–669.

[123] N. Kaminski, 2009 13th European Conference on Power Electronics and Applications **8** (2009).

[124] N. Kaminski and O. Hilt, IET Circuits, Devices & Systems **8**, 227 (2014).

[125] C. Buttay, D. Planson, B. Allard, D. Bergogne, P. Bevilacqua, C. Joubert, M. Lazar, C. Martin, H. Morel, D. Tournier, and C. Raynaud, Materials Science and Engineering: B **176**, 283 (2011).

[126] S. Fujita, Japanese Journal of Applied Physics **54**, 030101 (2015).

[127] P. G. Neudeck, in *Extreme Environment Electronics* (CRC Press, Taylor & Francis Group, 2013) pp. 225–232.

[128] A. Hassan, Y. Savaria, and M. Sawan, IEEE Access **6**, 78790 (2018).

[129] M. Higashiwaki, K. Sasaki, A. Kuramata, T. Masui, and S. Yamakoshi, physica status solidi (a) **211**, 21 (2014).

[130] G. Liu, B. R. Tuttle, and S. Dhar, Applied Physics Reviews **2**, 021307 (2015).

[131] S. Rybalka, E.Yu. Krayushkina, A. Demidov, O. Shishkina, and B. Surin, International Journal of Physical Research **5**, 11 (2017).

[132] C. Darmody and N. Goldsman, Journal of Applied Physics **126**, 145701 (2019).

[133] V. J. B. Torres, I. Capan, and J. Coutinho, Physical Review B **106**, 224112 (2022).

[134] S. J. Pearton, J. Yang, P. H. Cary, F. Ren, J. Kim, M. J. Tadjer, and M. A. Mastro, Applied Physics Reviews **5**, 011301 (2018).

[135] V. Soler, *Design and Process Developments towards an Optimal 6.5 kV SiC Power MOSFET*, Ph.D. thesis, Universitat Politecnica de Catalunya (2019).

[136] M. Yoder, IEEE Transactions on Electron Devices **43**, 1633 (Oct./1996).

[137] S. Rao, E. D. Mallemace, and F. G. Della Corte, Electronics **11**, 1839 (2022).

[138] G. Sozzi, M. Puzzanghera, R. Menozzi, and R. Nipoti, IEEE Transactions on Electron Devices **66**, 3028 (2019).

[139] R. Nipoti, G. Sozzi, M. Puzzanghera, and R. Menozzi, MRS Advances **1**, 3637 (2016).

[140] M. Usman and M. Nawaz, Solid-State Electronics **92**, 5 (2014).

[141] F. Pezzimenti, IEEE Transactions on Electron Devices **60**, 1404 (2013).

[142] S. Bellone, F. G. Della Corte, L. F. Albanese, and F. Pezzimenti, IEEE Transactions on Power Electronics **26**, 2835 (2011).

[143]D. Schröder, *Leistungselektronische Bauelemente* (Springer Berlin Heidelberg, Berlin, Heidelberg, 2006).

[144]X. Dong, M. Huang, Y. Ma, C. Fu, M. He, Z. Yang, Y. Li, and M. Gong, IEEE Transactions on Nuclear Science , 1 (2024).

[145]T. Yang, C. Fu, W. Song, Y. Tan, S. Xiao, C. Wang, K. Liu, X. Zhang, and X. Shi, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **1056**, 168677 (2023).

[146]T. Yang, Y. Tan, C. Wang, X. Zhang, and X. Shi, "Simulation of the 4H-SiC Low Gain Avalanche Diode," (2022), arXiv:2206.10191 [physics].

[147]M. De Napoli, Frontiers in Physics **10**, 898833 (2022).

[148]M. Cabello, V. Soler, G. Rius, J. Montserrat, J. Rebollo, and P. Godignon, Materials Science in Semiconductor Processing **78**, 22 (2018).

[149]Q. Chen, L. Yang, S. Wang, Y. Zhang, Y. Dai, and Y. Hao, Applied Physics A **118**, 1219 (2015).

[150]H. A. Mantooth, in *Extreme Environment Electronics* (CRC Press, Taylor & Francis Group, 2013) pp. 243–252.

[151]L. F. Albanese, *Characterization, Modeling and Simulation of 4H-SiC Power Diodes*, Ph.D. thesis, UniversitàdegliStudidiSalerno (2010).

[152]P. Bhatnagar, A. B. Horsfall, N. G. Wright, C. M. Johnson, K. V. Vassilevski, and A. G. O'Neill, Solid-State Electronics **49**, 453 (2005).

[153]M. W. Cole and P. Joshi, in *Silicon Carbide*, edited by Z. C. Feng and J. H. Zhao (Springer Berlin Heidelberg, Berlin, Heidelberg, 2004) pp. 517–536.

[154]H. Iwata and K. M. Itoh, Materials Science Forum **338–342**, 729 (2000).

[155]H. Iwata, K. M. Itoh, and G. Pensl, Journal of Applied Physics **88**, 1956 (2000).

[156]N. Wright, in *IEE Colloquium on New Developments in Power Semiconductor Devices*, Vol. 1996 (IEE, London, UK, 1996) pp. 6–6.

[157]H.-E. Nilsson, U. Sannemo, and C. S. Petersson, Journal of Applied Physics **80**, 3365 (1996).

[158]I. Neila Inglesias, "APPLYING NUMERICAL SIMULATION TO MODELS SiC SEMICONDUCTOR DEVICES," (2012).

[159]T. Kimoto, Japanese Journal of Applied Physics **54**, 040103 (2015).

[160]J. Zhao, X. Li, K. Tone, P. Alexandrov, M. Pan, and M. Weiner, Solid-State Electronics **47**, 377 (2003).

[161]A. Elasser, M. Kheraluwala, M. Ghezzo, R. Steigerwald, N. Evers, J. Kretchmer, and T. Chow,

IEEE Transactions on Industry Applications **39**, 915 (2003).

[162] A. Elasser, M. Ghezzo, N. Krishnamurthy, J. Kretchmer, A. Clock, D. Brown, and T. Chow, Solid-State Electronics **44**, 317 (2000).

[163] V. Chelnokov and A. Syrkin, Materials Science and Engineering: B **46**, 248 (1997).

[164] F. L. L. Nouketcha, Y. Cui, A. Lelis, R. Green, C. Darmody, J. Schuster, and N. Goldsman, IEEE Transactions on Electron Devices **67**, 3999 (2020).

[165] A. A. Lebedev, *Radiation Effects in Silicon Carbide*, Materials Research Foundations No. volume 6 (2017) (Materials Research Forum LLC, Millersville, PA, USA, 2017).

[166] T. P. Chow, I. Omura, M. Higashiwaki, H. Kawarada, and V. Pala, IEEE Transactions on Electron Devices **64**, 856 (2017).

[167] J. A. Pellish and L. M. Cohn, in *Extreme Environment Electronics* (CRC Press, Taylor & Francis Group, 2013) pp. 49–58.

[168] S. M. Sze and K. K. Ng, *Physics of Semiconductor Devices*, 3rd ed. (Wiley-Interscience, Hoboken, N.J, 2007).

[169] J. Millán, IET Circuits, Devices & Systems **1**, 372 (2007).

[170] A. Pérez-Tomás, P. Brosselard, P. Godignon, J. Millán, N. Mestres, M. R. Jennings, J. A. Covington, and P. A. Mawby, Journal of Applied Physics **100**, 114508 (2006).

[171] T. P. Chow, N. Ramungul, J. Fedison, and Y. Tang, in *Silicon Carbide*, edited by W. J. Choyke, H. Matsunami, and G. Pensl (Springer Berlin Heidelberg, Berlin, Heidelberg, 2004) pp. 737–767.

[172] N. Zhang, *High Voltage GaN HEMTs with Low On-Resistance for Switching Applications*, Ph.D. thesis, UNIVERSITY of CALIFORNIA, Santa Barbara (2002).

[173] R. Trew, Proceedings of the IEEE **90**, 1032 (2002).

[174] S. K. Lee, *Processing and Characterization of Silicon Carbide (6H-SiC and 4H-SiC) Contacts for High Power and h...* (Mikroelektronik och informationsteknik, Kista, 2002).

[175] R. Kemerley, H. Wallace, and M. Yoder, Proceedings of the IEEE **90**, 1059 (2002).

[176] V. Dmitriev, T. P. Chow, S. P. DenBaars, M. S. Shur, and M. G. Spencer, "High-Temperature Electronics in Europe:," Tech. Rep. (Defense Technical Information Center, Fort Belvoir, VA, 2000).

[177] T. Chow, V. Khemka, J. Fedison, N. Ramungul, K. Matocha, Y. Tang, and R. Gutmann, Solid-State Electronics **44**, 277 (2000).

[178] C. M. Zetterling, M. Östling, C. I. Harris, N. Nordell, K. Wongchotigul, and M. G. Spencer,

Materials Science Forum **264–268**, 877 (1998).

[179] P. B. Shah and K. A. Jones, Journal of Applied Physics **84**, 4625 (1998).

[180] M. Roschke, F. Schwierz, G. Paasch, and D. Schipanski, Materials Science Forum **264–268**, 965 (1998).

[181] E. Danielsson, C. I. Harris, C. M. Zetterling, and M. Östling, Materials Science Forum **264–268**, 805 (1998).

[182] T. P. Chow, N. Ramungul, and M. Ghezzo, MRS Proceedings **483**, 89 (1997).

[183] T. P. Chow and M. Ghezzo, MRS Proceedings **423**, 9 (1996).

[184] B. Ozpineci, "Comparison of Wide-Bandgap Semiconductors for Power Electronics Applications," Tech. Rep. ORNL/TM-2003/257, 885849 (2004).