Received 21 April 2022; revised 12 July 2022; accepted 13 July 2022. Date of publication 15 July 2022; date of current version 28 July 2022.
The review of this article was arranged by Editor G. I. Ng.

Digital Object Identifier 10.1109/JEDS.2022.3191543

Piezoresistive Thermal Characteristics of Aluminum-Doped P-Type 3C-Silicon Carbides

TAKAYA SUGIURA[1] (Member, IEEE), NAOKI TAKAHASHI[1], RYOHEI SAKOTA[1], KAZUNORI MATSUDA[2], AND NOBUHIKO NAKANO[1] (Member, IEEE)

1 Department of Electronics and Electrical Engineering, Keio University, Yokohama 223-8522, Japan
2 Division of Electrical, Electronic and Infocommunications Engineering, Graduate School of Engineering, Osaka University, Suita 565-0871, Japan

CORRESPONDING AUTHOR: T. SUGIURA (e-mail: takaya_sugiura@nak.elec.keio.ac.jp)

(Takaya Sugiura and Naoki Takahashi are co-first authors.)

ABSTRACT This study examined the temperature-related piezoresistance issues of p-type doped 3C-silicon carbide (3C-SiC) materials. Previously, we proposed piezoresistance temperature models that describe phenomena based on the ionization energies of materials oriented for high-temperature operations. This study aimed to determine the ionization energy as a function of the aluminum doping concentration of 3C-SiC. However, at the low-temperature region a drastic decrease in the piezoresistive coefficient was observed, and it was predicted to occur when materials possessing large impurity ionization energy are used under negative thermal strained conditions. This phenomenon is in contrast to the conventional piezoresistance factor $P(N, T)$ that is based on narrow band-gap materials such as silicon or germanium; thus, it provides new insights into low-temperature piezoresistance phenomena.

INDEX TERMS 3C-SiC, aluminum acceptor, device simulation, piezoresistance, temperature, wide band-gap semiconductors.

I. INTRODUCTION

Wide band-gap (WBG) semiconductors such as silicon carbide (SiC) are crucial to the power electronics field owing to their excellent material properties of high breakdown robustness and temperature tolerance, which improve the reliability of semiconductor devices [1], [2]. Among the material properties, there exist both advantages and disadvantages for electron devices. The incomplete ionization is an important physics concept in WBG semiconductors because the impurity levels are formed at deeper levels from the conductive or the valence band as compared with silicon [3]. Moreover, the free carrier concentration must be reconsidered using the ionization energy of the dopant [4]. Incomplete ionization affects device reliability, which can further cause a high electric field and device breakdowns [5], [6].

In particular, acceptor doping presents serious problems owing to its larger ionization energy [3], [5]. At room temperature, the activation ratio of the acceptor dopant is extremely small and the free carrier concentration is much smaller than the intended doping concentration. Therefore, the design of WBG material-based electron devices with optimized performance and sufficient reliability must consider this effect. Among WBG materials, SiC is one the most attractive materials for robustness against severe conditions such as high temperatures, mechanical stresses, and chemical corrosions. SiC has several polytypes, with 4H-, 6H-, 2H-, 3C- and 15R- being the major ones. Among these polytypes the 4H-, 6H- and 3C-SiC are commonly used. Currently, 4H- and 6H- are the primary targets of research; however, the 3C-SiC polytype offers unique potential in the power electronics field or in micro electromechanical systems (MEMS), with its narrower band-gap energy of approximately 2.2 eV [7]–[9]. The most important acceptor for 3C-SiC is aluminum because it is known to have the smallest ionization energy [9]. However, the ionization energy strongly depends on the doping concentration [3], [4], and this aspect has not been well researched for 3C-SiC.

We previously proposed a method to determine the ionization energy from the temperature response of the piezoresistive effect [10], which is useful for determining

This work is licensed under a Creative Commons Attribution 4.0 License. For more information, see https://creativecommons.org/licenses/by/4.0/

TABLE 1. Simulation modeling of 3C-SiC.

Physics	Value
Crystal direction [13], [14]	<110>
Young's modulus E **[GPa]** [15]	330
Poisson's ratio γ [16]	0.267
Thermal expansion coefficient α_T **[1/K]** [17]	$5 \times 10^{-9}T + 2 \times 10^{-6}$
Bandgap energy E_{g0} **[eV]** [9]	2.39
Bandgap energy parameter α **[eV/K]** [9]	6.00×10^{-3}
Bandgap energy parameter β **[K]** [9]	1,200
Doping concentration N_d **[cm^{-3}]** [13], [14]	5×10^{18}, 2×10^{19} (p-type)
Temperature dependence of mobility [18]	$(T/300)^{-2.5}$

the ionization energy under several conditions, including different doping concentrations. This study aimed to determine the doping concentration dependence of the ionization energy of 3C-SiC with an aluminum acceptor. The ionization energy determinations were made based on the gauge factor (GF) measurements for different temperatures. Moreover, after combining the reported values it was determined as a function of doping level. However, simulations with insertions of ionization energy revealed drastic decreases in piezoresistive coefficients at low-temperature environments. This is in contrast to the generally known piezoresistance factor $P(N, T)$, which expresses increases in piezoresistive coefficients with decreases in temperature [11], [12]. It is predicted that the acceptor doping in WBG semiconductors can result in this phenomenon, owing to its larger ionization energy beyond $3kT$ (k is the Boltzmann's constant and T is the temperature) at low-temperature environments. Although further research is required, these results can provide new insights concerning low-temperature oriented physics in this field.

II. UNDERLYING PHYSICS

A. INCOMPLETE IONIZATION

Incomplete ionization is important for WBG materials other than silicon devices [3]–[5]. The doping for these materials forms deep dopant levels that are higher than the thermal energy kT. Therefore, at room temperature, the thermal energy is not sufficient to activate all dopants, and the free carrier concentration becomes smaller than the intended doping concentration. The energy between the dopant level and the conductive or the valence band is referred to as 'ionization energy' or 'activation energy' ('ionization energy' is used herein).

This effect is relatively prominent for an acceptor that forms much deeper-lying impurity levels as compared with donor doping. For SiC, the acceptor has an ionization energy larger than 100 meV, which implies that most dopants do not provide free carriers; this affects fundamental device operations. The most common acceptor dopant in SiC is aluminum; however, its ionization energy is higher than 200 meV [9] at the shallow-doped region. The ionization energy is affected by the doping concentration, and heavy-doping tends to lower it [3]. From a certain perspective, this effect can affect even the reliability of the device [5]; this is particularly serious for power electronics that require robustness against high voltages or high temperatures.

B. PIEZORESISTIVE EFFECT

The piezoresistive effect presents the resistivity change of a material under stressed conditions [19], and its primary application is mechanical stress sensing that features high sensitivity and good linearity against the applied force. The expression of the resistivity change is expressed as

$$\frac{\Delta R}{R\varepsilon} = \pi_l \sigma_l + \pi_t \sigma_t. \tag{1}$$

where R is the resistance of the material, ε is the applied strain, and π and σ are the piezoresistive coefficient and the stress, respectively (each suffix of 'l' and 't' corresponds to the longitudinal and the transverse direction).

The increase in the temperature results in a decrease in the piezoresistive coefficient, and our previous work found that the temperature dependence of the value is determined by the ionization energy [10]. The ionization energy of the material E_{mat} is expressed by using the ionization energy of boron in silicon E_{Si} and the temperature dependence of the piezoresistive coefficient against T_0/T (T_0 is the room temperature) at the linear region; a_{mat} as

$$E_{mat} = \frac{1}{a_{mat}} E_{Si}. \tag{2}$$

where the value E_{Si} is 43.3 meV [20]. This expression enables the determination of the ionization energy from the temperature dependence of the piezoresistive effect.

III. SIMULATION MODELING

The simulation was based on 2D modeling, including the mechanical stress simulation for obtaining the stress profiles and the electrical simulation for calculating the I–V characteristics under applied stress.

The mechanical stress simulation was performed using COMSOL Multiphysics Ver5.5 [21]. The electrical simulation was conducted using the original device simulator wherein the piezoresistive mobility model was implemented [22], [23]. The simulation considered thermal expansion that is related to the temperature variation. Strain reference temperature of 20 °C is used for expressing thermal expansion [21]. Therefore, when the temperature is higher than this the material expands and shrinks at the lower temperature [24]. The validity of the proposed simulation modeling has already been verified in a previous work [10], and the same modeling was applied in this study. The effective mass of 1.32 for the holes was used in this study to account for the crystal orientation in <110> [25].

IV. RESULTS AND DISCUSSION

A. ALUMINUM-DOPANT IONIZATION ENERGY IN 3C-SIC

The determination of the ionization energies is detailed first. Our previous work showed that the GF and piezoresistive coefficient exhibit the same trends against the temperature ratio T_0/T. Therefore, the ionization energies were estimated on the basis of the experimental results. Experiments that investigated the piezoresistive temperature response for two doping concentrations—5×10^{18} cm^{-3} and 2×10^{19} cm^{-3}

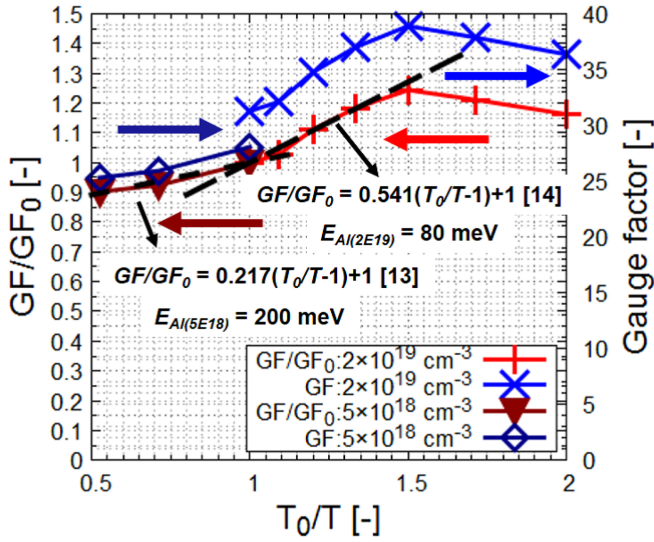

FIGURE 1. Temperature responses of the gauge factor ratios [13], [14] and corresponding ionization energies.

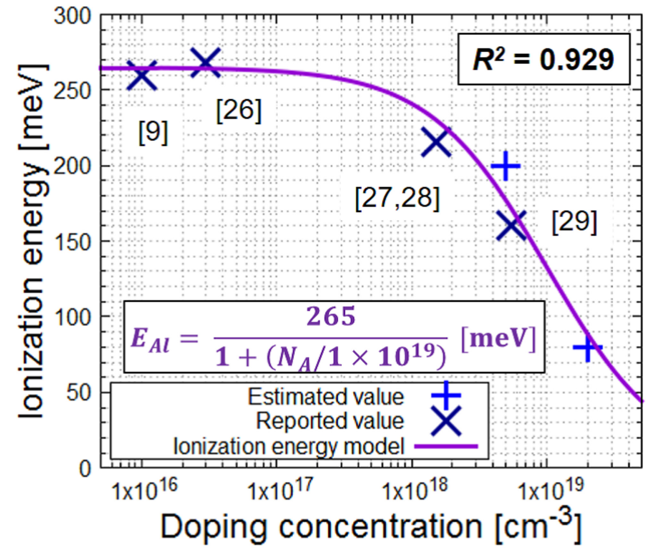

FIGURE 2. Ionization energy of the aluminum dopant in 3C-SiC as a function of doping concentration.

were examined [13], [14]. Experimental data from references [13], [14] were used to fit the simulation results in terms of gauge factor, doping density, and ionization energy. It resulted in the following conclusion. Figure 1 shows the temperature responses of the GF ratios against T_0/T for the doping concentrations of 5×10^{18} cm^{-3} and 2×10^{19} cm^{-3}. Using the GF values and the GF at room temperature GF_0, the linear approximations of the two conditions are

$$GF/GF_0 = 0.217(T_0/T) + 0.779 \tag{3}$$

for 5×10^{18} cm^{-3} and

$$GF/GF_0 = 0.542(T_0/T) + 0.481 \tag{4}$$

for 2×10^{19} cm^{-3}, respectively. Here, for 2×10^{19} cm^{-3} the linear approximation was estimated until a temperature of 200 K was reached, and the decrease in GF values with temperature was noted. Thus, on the basis of these approximations, the ionization energy can be determined as follows: 200 meV for 5×10^{18} cm^{-3} ($E_{5\times10^{18}} = 43.3$ meV/0.217 = 200 meV) and 79.9 meV for 2×10^{19} cm^{-3} ($E_{5\times10^{18}} = 43.3$ meV/0.542 = 80 meV).

The determination of the ionization energy as a function of the doping concentration is the primary goal of this study. We used the reported ionization energies of 260 meV as the unintentionally-doped condition (treated as 1×10^{16} cm^{-3} in this study), 268 meV at the low-middle value corresponding to 10^{16} cm^{-3} (treated as 3×10^{16} cm^{-3} in this study), 216 meV at 1.5×10^{18} cm^{-3}, and 160 meV at 5.5×10^{18} cm^{-3}, mainly at the middle-doped region [9], [26]–[29]. The obtained result of the middle- and heavy-doped conditions enabled the derivation of the model, and the ionization energy expression was determined as the logistical style [3]. The expression of ionization energy E_{Al} (unit = meV) is

$$E_{Al} = \frac{265}{1 + \left(N_A/1 \times 10^{19}\right)}, \tag{5}$$

as a function of acceptor doping concentration N_A. The ionization energy data were concentrated at the middle-heavy doped region; however, the change of the ionization energy began at approximately 10^{18} cm^{-3}; therefore, the proposed ionization energy model was considered to be sufficiently reliable [3]. The R^2 value obtained was 0.929, which ensures the usefulness of the proposed expression.

B. PIEZORESISTIVE COEFFICIENT IN 3C-SIC

This study simulated the piezoresistive sensor phenomena using the derived ionization energies. The piezoresistive coefficients that reproduce the GF values of experiments [13], [14] were determined via numerical simulations.

As shown in Fig. 3, a drastic drop in the piezoresistive coefficient at the low-temperature region was observed. Further, large errors were observed between the realistic GF values and GF values calculated using the estimated piezoresistive coefficients from GF experiments. This result is in contrast to the high-temperature region, where the piezoresistive coefficient transition follows the GF value against the temperature, as shown in previous results [10] and the result of 5×10^{18} cm^{-3}. On the basis of these trends, a large GF was expected at low temperatures of 200–150 K; however, the realistic experimental results show relatively small GF values of approximately 30–40 [14]. The simulation considered the strain reference temperature (the temperature of thermal strain is zero) as 20 °C and it is considered that thermal shrinkage causes this phenomenon. At the shrunk condition, larger stress occurred inside the device causing strain, which in turn induced a larger piezoresistive effect, as shown in Fig. 4. This study used a Young's modulus of 330

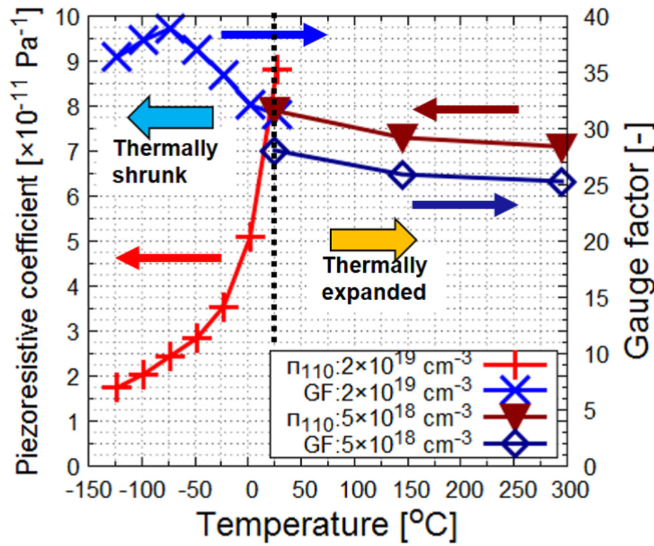

FIGURE 3. Piezoresistive coefficients against the temperature and corresponding gauge factors.

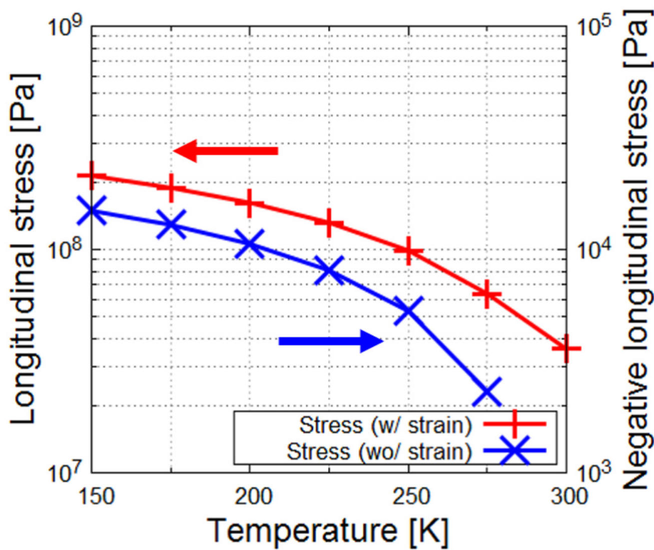

FIGURE 4. Longitudinal-direction stresses of w/strain (cantilever's 100 $\mu\varepsilon$) and w/o strain (only thermal strain) under the room temperature.

GPa, and the temperature dependence of Young's modulus in 3C-SiC is almost negligible [15]. However, the experimental results [14] indicate that the GF value is much smaller than the large longitudinal stress. Therefore, a small piezoresistive coefficient is necessary as the temperature lowers.

The results obtained at the low temperature were in contrast to the previous reports that considered the larger piezoresistive coefficient as the temperature decreases [11], [12]. In addition, the experimental results regarding p-type silicon also showed increased piezoresistive coefficients at the low temperature [30], [31], with these results appearing to follow the piezoresistance factor $P(N, T)$. Here, the treated material of 3C-SiC featured a wide band-gap, and the

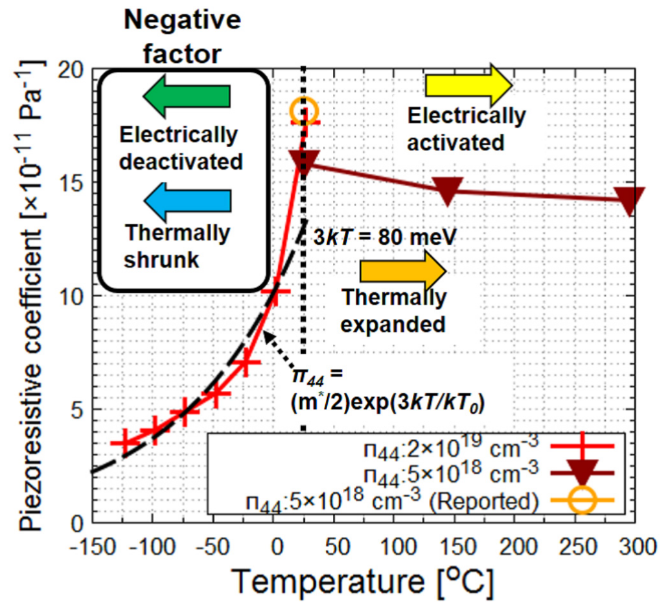

FIGURE 5. Piezoresistive coefficients π_{44} for two doping concentrations against the temperature.

ionization energy of the dopant, particularly for the acceptor, provides large ionization energy. Further, the predicted value based on GF is 80 meV. The energy of 80 meV is approximately identical to the thermal energy of $3kT$ at room temperature, wherein the value is 77.6 meV. Moreover, at room temperature, the piezoresistive coefficient becomes 8.8×10^{-11} Pa^{-1}; the value is almost equal to the reported value at 5×10^{18} cm^{-3} of 9.1×10^{-11} Pa^{-1}. Consequently, considering the smaller value with increases in the doping level, this value is considered to be reasonable [32]. The p-type silicon exhibited a maximum value of under 45 meV [33], and the corresponding thermal energy of $3kT$ was obtained at a temperature of 175 K ($\simeq$ –100 °C). The value of $3kT$ relates to degeneration; therefore, it was considered that the WBG semiconductors that provide the larger ionization energy, particularly for acceptors, are critical to this phenomenon. The results in [30], [31] are those of temperatures beyond it; therefore, it can be concluded that piezoresistive coefficient drops are avoided.

Low-temperature situations render activating carriers from the impurity level to the conductive (or valence) level challenging. The piezoresistive effect originates from the carrier activation enhancements. Therefore, in the low-temperature situations, the piezoresistive coefficient should be small because the carrier activation becomes difficult. The results of our previous work regarding high-temperature [10] showed that the piezoresistive coefficient transitions to GF values were followed even in cases of large ionization energy conditions such as p-type doped 4H-SiC (200 meV). Considering the difference, the mechanical stress factor can be another condition; under thermal shrinkage, the temperature is under the strain reference temperature of 20 °C.

In conclusion, there appears to be two conditions that result in a drop in the piezoresistive coefficient at low-temperature environments: 1) a smaller $3kT$ than the ionization energy, and 2) thermal shrinkage that occurs at a lower temperature than the strain reference temperature (in general it is 20 °C). Subsequently, we can estimate the 'negative effect' of both the electrical (thermal energy $3kT$ is smaller than impurity ionization energy) and mechanical (temperature is under the strain reference temperature and causes thermal shrinkage) effects corresponding to it.

Finally, from the results shown in Fig. 3, the piezoresistive coefficient element π_{44} in aluminum-doped 3C-SiC was determined. The <110> longitudinal piezoresistive coefficient can be approximated as $\pi_{44}/2$ by their small values of π_{11} and π_{12}, and the values in Fig. 5 were obtained by multiplying them. Regarding the results of 5×10^{18} cm^{-3}, the value at the room temperature was slightly smaller than the reported value [32]. This is because of the small GF experimental value at room temperature. However, it is reckoned that the obtained value is within the errors of GF experiments. Moreover, the piezoresistive coefficient at low temperatures varies exponentially as a function of thermal energy, as follows:

$$\pi_{44} = \frac{m^*_{e,h}}{2} \cdot \exp\left(\frac{3kT}{kT_0}\right). \quad (6)$$

until the temperature at which $3kT = 80$ meV, the value of E_{imp}. It is considered that the π_{44} corresponds to the shear orientation. Therefore, at the thermally shrunk condition, this shear-oriented piezoresistance is weakened and appears as the small piezoresistive coefficient. Further, considering the large π_{44} that appears at the p-type doping [34], this phenomenon becomes important for p-type doped semiconductors. Impurity ionization is determined by the ionization energy and effective mass of the material [4], and this function expresses the decrease in thermal energy and the inability to activate the conduction (or valence) band.

In addition, an analytical report of silicon-based pressure sensors showed decreased output at low temperatures [35]. The report concerned p-type silicon, and although the change was relatively small compared to our results in the case of SiC, a similar phenomenon is observed; the results support the theory that the phenomenon becomes important for acceptor dopant that has a large ionization energy. However, regarding WBG materials that feature larger ionization energy, there is a paucity of studies [36], and further research is required to understand this phenomenon. However, the findings herein can provide new insights in this field related to the thermal effects of both electrical and mechanical issues.

V. CONCLUSION

This study evaluated the temperature-related issues of p-type 3C-SiC. First, the aluminum ionization energy in 3C-SiC was determined based on the GF temperature trends from experimental results, as $E_{Al} = 265/(1 + (N_A/1 \times 10^{19}))$. Second, the piezoresistive coefficients were determined and the values were observed to significantly drop at low-temperature environments. It was concluded that the mechanical factor of thermal shrinkage and the electrical factor of smaller thermal energy were responsible for this change. Furthermore, at the low temperature the piezoresistive coefficient follows the exponential shape of thermal energy and effective mass that relates to the magnitude of the carrier ionization rate. This phenomenon is expected to provide new insights in this field, and further studies are favorable.

ACKNOWLEDGMENT

The authors express their appreciation to Associate Prof. Hidetoshi Takahashi at Keio University for his kind advice.

REFERENCES

[1] J. Millán, P. Godignon, X. Perpiñà, A. Pérez-Tomás, and J. Rebollo, "A survey of wide bandgap power semiconductor devices," *IEEE Trans. Power Electron.*, vol. 29, no. 5, pp. 2155–2163, May 2014. [Online]. Available: https://doi.org/10.1109/TPEL.2013.2268900

[2] X. She, A. Q. Huang, Ó. Lucia, and B. Ozpineci, "Review of silicon carbide power devices and their applications," *IEEE Trans. Ind. Electron.*, vol. 64, no. 10, pp. 8193–8205, Oct. 2017. [Online]. Available: https://doi.org/10.1109/TIE.2017.2652401

[3] C. Darmody and N. Goldsman, "Incomplete ionization in aluminum-doped 4H-silicon carbide," *J. Appl. Phys.*, vol. 126, no. 14, Oct. 2019, Art. no. 145701. [Online]. Available: https://doi.org/10.1063/1.5120707

[4] G. Xiao, J. Lee, J. J. Liou, and A. Ortiz-Conde, "Incomplete ionization in a semiconductor and its implications to device modeling," *Microelectron. Rel.*, vol. 39, no. 8, pp. 1299–1303, Aug. 1999. [Online]. Available: https://doi.org/10.1016/S0026-2714(99)00027-X

[5] N. Donato and F. Udrea, "Static and dynamic effects of the incomplete ionization in superjunction devices," *IEEE Trans. Electron Devies*, vol. 65, no. 10, pp. 4469–4475, Oct. 2018. [Online]. Available: https://doi.org/10.1109/TED.2018.2867058

[6] Q. Chen, W. He, C. Cheng, and Y. Xue, "Theoretical investigation of incomplete ionization of dopants effect on p+nn-n+ 4H-SiC IMPATT diode," *J. Phys. Conf. Ser.*, vol. 1649, Aug. 2020, Art. no. 12048. [Online]. Available: https://doi.org/10.1088/1742-6596/1649/1/012048

[7] T. Kimoto, "Material science and device physics in SiC technology for high-voltage power devices," *Jpn. J. Appl. Phys.*, vol. 54, no. 4, Mar. 2015, Art. no. 40103. [Online]. Available: https://doi.org/10.7567/JJAP.54.040103

[8] M. Bhatnagar and B. J. Baliga, "Comparison of 6H-SiC, 3C-SiC, and Si for power devices," *IEEE Trans. Electron Devices*, vol. 40, no. 3, pp. 645–655, Mar. 1993. [Online]. Available: https://doi.org/10.1109/16.199372

[9] A. Arvanitopoulos, N. Lophitis, S. Perkins, K. N. Gyftakis, M. B. Guadas, and M. Antoniou, "Physical parameterisation of 3C-silicon carbide (SiC) with scope to evaluate the suitability of the material for power diodes as an alternative to 4H-SiC," in *Proc. IEEE 11th Int. Symp. Diagn. Electr. Mach. Power Electron. Drives (SDEMPED)*, Aug. 2017, pp. 565–571. [Online]. Available: https://doi.org/10.1109/DEMPED.2017.8062411

[10] T. Sugiura, N. Takahashi, R. Sakota, K. Matsuda, and N. Nakano, "High-temperature piezoresistance of silicon carbide and gallium nitride materials," *IEEE J. Electron. Devices Soc.*, vol. 10, pp. 203–211, 2022. [Online]. Available: https://doi.org/10.1109/JEDS.2022.3150915

[11] Y. Kanda, "A graphical representation of the piezoresistance coefficients in silicon," *IEEE Trans. Electron Devices*, vol. ED-29, no. 1, pp. 64–70, Jan. 1982. [Online]. Available: https://doi.org/10.1109/T-ED.1982.20659

[12] J. Richter, J. Pedersen, M. Brandbyge, E. V. Thomsen, and O. Hansen, "Piezoresistance in *p*-type silicon revisited," *J. Appl. Phys.*, vol. 104, no. 2, Jul. 2008, Art. no. 23715. [Online]. Available: https://doi.org/10.1063/1.2960335

[13] H.-P. Phan *et al.*, "Piezoresistive effect in p-type 3C-SiC at high temperatures characterized using joule heating," *Sci. Rep.*, vol. 6, Jun. 2016, Art. no. 28499. [Online]. Available: https://doi.org/10.1038/srep28499

[14] H. Phan *et al.*, "Characterization of the piezoresistance in highly doped p-type 3C-SiC at cryogenic temperatures," *RSC Adv.*, vol. 8, no. 52, pp. 29976–29979, Aug. 2018. [Online]. Available: https://doi.org/10.1039/C8RA05797D

[15] F. Iacopi, G. Walker, L. Wang, L. Malesys, S. Ma, B. V. Cunning, and A. Iacopi, "Orientation-dependent stress relaxation in hetero-epitaxial 3C-SiC films," *Appl. Phys. Lett.*, vol. 102, no. 1, Jan. 2013, Art. no. 11908. [Online]. Available: https://doi.org/10.1063/1.4774087

[16] A. Samanta and I. Grinberg, "Investigation of Si/3C-SiC interface properties using classical molecular dynamics," *J. Appl. Phys.*, vol. 124, no. 17 Nov. 2018, Art. no. 175110. [Online]. Available: https://doi.org/10.1063/1.5042203

[17] D. N. Talwar and J. C. Sherbondy, "Thermal expansion coefficient of 3C-SiC," *Appl. Phys. Lett.*, vol. 67, no. 22, pp. 3301–3303, Nov. 1995. [Online]. Available: https://doi.org/10.1063/1.115227

[18] M. Roschke and F. Schwierz, "Electron mobility models for 4H, 6H, and 3C SiC [MESFETs]," *IEEE Trans. Electron. Devices*, vol. 48, no. 7, pp. 1442–1447, Jul. 2001. [Online]. Available: https://doi.org/10.1109/16.930664

[19] A. A. Barlian, W.-T. Park, J. R. Mallon, Jr., A. J. Rastegar, and B. L. Pruitt, "Review: Semiconductor piezoresistance for microsystems," *Proc. IEEE*, vol. 97, no. 3, pp. 513–552, Mar. 2009. [Online]. Available: https://doi.org/10.1109/JPROC.2009.2013612

[20] C. Xiao, D. Yang, X. Yu, L. Xiang, and D. Que, "Determination of the boron and phosphorus ionization energies in compensated silicon by temperature-dependent luminescence," *Silicon*, vol. 9, pp. 147–151, May 2017. [Online]. Available: https://doi.org/10.1007/s12633-014-9193-3

[21] *COMSOL Multiphysics Ver5.5*, COMSOL Inc., Stockholm, Sweden, 2019.

[22] T. Sugiura, N. Takahashi, and N. Nakano, "Evaluation of p-type 4H-SiC piezoresistance coefficients in (0001) plane using numerical simulation," *Mater. Sci. Forum*, vol. 1004, pp. 249–255, Jul. 2020. [Online]. Available: https://doi.org/10.4028/www.scientific.net/MSF.1004.249

[23] T. Sugiura, N. Takahashi, and N. Nakano, "The piezoresistive mobility modeling for cubic and hexagonal silicon carbide crystals," *J. Appl. Phys.*, vol. 127, no. 24, Jun. 2020, Art. no. 245113. [Online]. Available: https://doi.org/10.1063/5.0006830

[24] A. Tanguy, Y. Li, and M. Tan, "Research on testing methods of temperature strain and force strain under extreme temperature environment," in *Proc. IOP Conf. Ser. Earth Environ. Sci.*, vol. 668, Feb. 2021, Art. no. 12067. [Online]. Available: https://doi.org/10.1088/1755-1315/668/1/012067

[25] C. Persson and U. Lindefelt, "Relativistic band structure calculation of cubic and hexagonal SiC polytypes," *J. Appl. Phys.*, vol. 82, no. 11, pp. 5496–5508, Aug. 1997. [Online]. Available: https://doi.org/10.1063/1.365578

[26] I. G. Ivanov, A. Henry, F. Yan, W. J. Choyke, and E. Janzén, "Ionization energy of the phosphorus donor in 3C-SiC from the donor-acceptor pair emission," *J. Appl. Phys.*, vol. 108, no. 6, Sep. 2010, Art. no. 63532. [Online]. Available: https://doi.org/10.1063/1.3487480

[27] M. Ikeda, H. Matsunami, and T. Tanaka, "Site effect on the impurity levels in 4H, 6H, and 15R SiC," *Phys. Rev. B, Condens. Matter*, vol. 22, no. 6, pp. 2842–2854, Sep. 1980. [Online]. Available: https://doi.org/10.1103/PhysRevB.22.2842

[28] A. A. Lebedev *et al.*, "Highly doped p-type 3C-SiC on 6H-SiC substrates," *Semicond. Sci. Technol.*, vol. 23, no. 7, May 2008, Art. no. 75004. [Online]. Available: https://doi.org/10.1088/0268-1242/23/7/075004

[29] M. Yamanaka, H. Daimon, E. Sakuma, S. Misawa, and S. Yoshida, "Temperature dependence of electrical properties of $n-$ and $p-type$ 3C-SiC," *J. Appl. Phys.*, vol. 61, no. 2, pp. 599–603, Jan. 1987. [Online]. Available: https://doi.org/10.1063/1.338211

[30] C.-H. Cho, R. C. Jaeger, and J. C. Suhling, "Characterization of the temperature dependence of the piezoresistive coefficients of silicon from -150 °C to $+125$ °C," *IEEE Sensors J.*, vol. 8, no. 8, pp. 1455–1468, Aug. 2008. [Online]. Available: https://doi.org/10.1109/JSEN.2008.923575

[31] A. Bosseboeuf *et al.*, "Thermal and electromechanical characterization of top-down fabricated p-type silicon nanowires," *Adv. Nat. Sci. Nanosci. Nanotechnol.*, vol. 6, no. 2, Feb. 2015, Art. no. 25001. [Online]. Available: https://doi.org/10.1088/2043-6262/6/2/025001

[32] H.-P. Phan *et al.*, "Fundamental piezoresistive coefficients of p-type single crystalline 3C-SiC," *Appl. Phys. Lett.*, vol. 104, no. 11, Mar. 2014, Art. no. 111905. [Online]. Available: https://doi.org/10.1063/1.4869151

[33] P. P. Altermatt, A. Schenk, B. Schmithüsen, and G. Heiser, "A simulation model for the density of states and for incomplete ionization in crystalline silicon. II. Investigation of Si:As and Si:B and usage in device simulation," *J. Appl. Phys.*, vol. 100, no. 11, Dec. 2006, Art. no. 113715. [Online]. Available: https://doi.org/10.1063/1.2386935

[34] H.-P. Phan, D. V. Dao, K. Nakamura, S. Dimitrijev, and N.-T. Nguyen, "The piezoresistive effect of SiC for MEMS sensors at high temperatures: A review," *IEEE J. Microelectromech. Syst.*, vol. 24, no. 6, pp. 1663–1677, Dec. 2015. [Online]. Available: https://doi.org/10.1109/JMEMS.2015.2470132

[35] M. Nie and Y. Gao, "The analytical calibration model of temperature effects on a silicon piezoresistive pressure sensor," *AIP Adv.*, vol. 7, no. 3, Mar. 2017, Art. no. 35120. [Online]. Available: https://doi.org/10.1063/1.4973333

[36] T. Wejrzanowski, E. Tymicki, T. Plocinski, J. J. Bucki, and T. L. Tan, "Design of SiC-doped piezoresistive pressure sensor for high-temperature applications," *Sensors*, vol. 21, no. 18, Sep. 2021, Art. no. 6066. [Online]. Available: https://doi.org/10.3390/s21186066

TAKAYA SUGIURA (Member, IEEE) received the B.S., M.S., and Ph.D. degrees in electrical engineering from Keio University, Yokohama, Kanagawa, in 2016, 2018, and 2021, respectively, where he is currently a Researcher with the Department of Electronics and Electrical Engineering. His research interests include c-Si solar cells, piezoresistive devices, photonics devices, and power electronics. He has been a member of the Electron Devices Society, Power Electronics Society, and Photonics Society since 2022.

NAOKI TAKAHASHI received the B.S. and M.S. degrees in electrical engineering from Keio University, Yokohama, Kanagawa, in 2019 and 2021, respectively, where he is currently pursuing the master's degree with the School of Integrated Design Engineering, Graduate School of Science and Technology. His research interests include the evaluation of the piezoresistive effect of wide band-gap cubic semiconductor materials using numerical simulations.

RYOHEI SAKOTA received the B.S. degree in electrical engineering from Keio University, Yokohama, Kanawaga, in 2021. His research interests include the evaluation of the piezoresistive effect of silicon carbide material using numerical simulations.

JOURNAL OF THE
ELECTRON DEVICES SOCIETY

KAZUNORI MATSUDA received the Ph.D. degree from Tsukuba University in 1993. From 2000 to 2003, he collaborated with Professor Karl Hess's Group, UIUC for simulations on hot carriers and reliability of MOSFET. He has been a Professor with the Department of Nano Material and Bio Engineering, Tokushima Bunri University since 2022. He is currently an Invited Professor with the Division of Electrical, Electronic and Infocommunications Engineering Graduate School of Engineering, Osaka University. He is currently working on wide-bandgap semiconductors. His research interests include transport phenomena in strained semiconductors and their applications.

NOBUHIKO NAKANO (Member, IEEE) was born in 1968. He received the B.S., M.S., and Ph.D. degrees in electrical engineering from Keio University, Japan, in 1990, 1992, and 1995, respectively. In 1996, he joined the Department of Electronics and Electrical Engineering, Keio University, as an Instructor, where he is currently a Professor with the Faculty of Science and Technology, Department of Electronics and Electrical Engineering. He is currently working on the design of an on-chip microsystem and bio-medical LSIs. His research interests include LSI/TCAD, numerical simulations, and modeling.