Title

Time Resolution Characterization of 4H-SiC LGADs With a 90Sr Source

Journal

IEEE Transactions on Nuclear Science, 73(2)

ISSN

0018-9499

Authors

Yang, Tao
Satapathy, Yashas
Sekely, Ben J
et al.

Publication Date

2026-02-01

DOI

10.1109/tns.2025.3646114

Time Resolution Characterization of 4H-SiC LGADs with a ^{90}Sr Source

Tao Yang, Yashas Satapathy, Ben J. Sekely, Abraham Tishelman-Charny, Greg Allion, Gil Atar, Philip Barletta, Carl Haber, Steve Holland, John F. Muth, Spyridon Pavlidis, and Stefania Stucci

***Abstract*—This work presents timing measurements of 4H-SiC Low Gain Avalanche Detectors (4H-SiC LGADs) using beta particles from a ^{90}Sr source. The 4H-SiC LGADs exhibit fast signal responses, and a time resolution of 61 ps was achieved, comparable to that of standard Si LGADs. The present limitation in the time resolution of 4H-SiC LGADs appears to stem from limited charge generation. Nevertheless, their higher voltage tolerance and faster carrier drift suggest that, with increased charge collection, their timing performance could approach or even surpass that of Si LGADs. These results demonstrate the strong potential of 4H-SiC LGADs as a robust platform for precision timing in future 4D tracking detectors, while also highlighting that signal charge is the dominant factor currently limiting their performance, indicating that further optimization of gain and drift structures will be essential for future development.**

***Index Terms*—4H-SiC, LGAD, time resolution, beta particle, MIPs**

I. Introduction

As a wide bandgap semiconductor, 4H-SiC has attracted increasing attention in recent years for its potential application in collider detectors [1], [2], due to its low leakage current, fast carrier saturation drift velocity, and excellent thermal stability [3]. However, the relatively small signal charge generated by minimum ionizing particles (MIPs) (only about 2/3 that of silicon [4]), along with the technical challenges associated with growing high-quality, low-doped epitaxial SiC epitaxial layers, have limited the widespread adoption of SiC detectors in high-energy physics experiments.

Previous experimental results have shown that conventional SiC PiN devices already achieve a time resolution with a hundred picoseconds [3], [5], [6]. However, the relatively small charge signal imposes significant challenges in achieving fast single-MIP detection with time resolution better than 100 ps for SiC devices. Inspired by the success of Si LGADs [7]–[12], a promising solution to these limitations is the development of 4H-SiC Low Gain Avalanche Detectors (4H-SiC LGADs) [13], [14]. 4H-SiC LGADs not only provide enhanced signal charges through internal gain, but also inherit the intrinsic material advantages of SiC and the excellent timing performance of the LGAD architecture, making them highly suitable for applications in 4D tracking. Recently, 4H-SiC LGADs have been successfully fabricated [15], and their excellent timing performance with better than 35 ps time resolution has been demonstrated using the ultraviolet transient current technique (UV-TCT) [16]. Building upon these previous results, this work characterizes the time resolution of 4H-SiC LGADs using beta particles from a ^{90}Sr source, demonstrating its potential for effective use in timing applications with MIPs.

This work is supported by the U.S. Department of Energy, Office of Science, Office of High Energy Physics, under Contract Number DE-AC02-05CH11231 and Award Number DE-SC0024252. Additional support was performed in part at the NCSU Nanofabrication Facility (NNF), a member of the North Carolina Research Triangle Nanotechnology Network (RTNN), which is supported by the National Science Foundation (Grant ECCS-1542015) as part of the National Nanotechnology Coordinated Infrastructure (NNCI).

Tao Yang, Steve Holland and Carl Haber are with Physics Division, Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, 94720, CA, U.S (e-mail: chhaber@lbl.gov).

Ben J. Sekely, Yashas Satapathy, Greg Allion, Gil Atar, Philip Barletta, Spyridon Pavlidis and John F. Muth are with Department of Electrical and Computer Engineering, North Carolina State University, 2410 Campus Shore Dr, Raleigh, 27606, NC, U.S. (e-mail: muth@ncsu.edu).

Stefania Stucci and Abraham Tishelman-Charny are with Brookhaven National Laboratory, 98 Rochester St, Upton, 11973, NY, U.S.

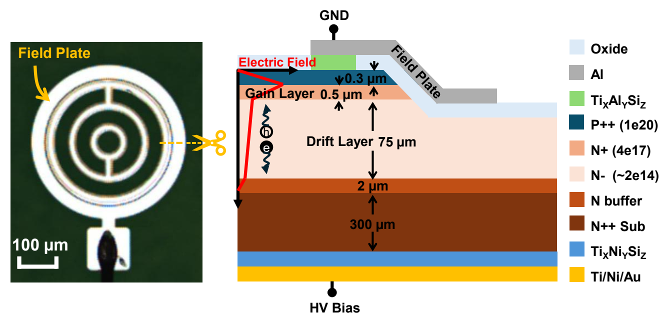

Fig. 1. Photograph of the 300 μm thick 4H-SiC LGAD (left) and diagram of the cross-sectional view of the device (right).

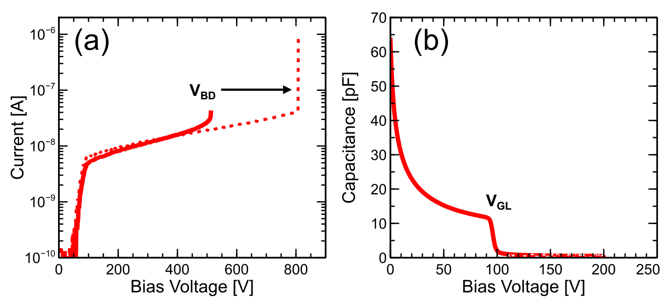

Fig. 2. (a) I–V characteristics of the 300 μm 4H-SiC LGAD at room temperature. The solid line shows the original I–V characteristics of the device before any testing, while the dashed line shows the I–V curve of the same device after several days of signal testing under high bias voltage.; (b) C–V characteristics of the 300 μm 4H-SiC LGAD.

II. Device Characteristics

A single 4H-SiC LGAD used for this study and a schematic illustration of its cross-sectional structure are shown in Fig. 1.

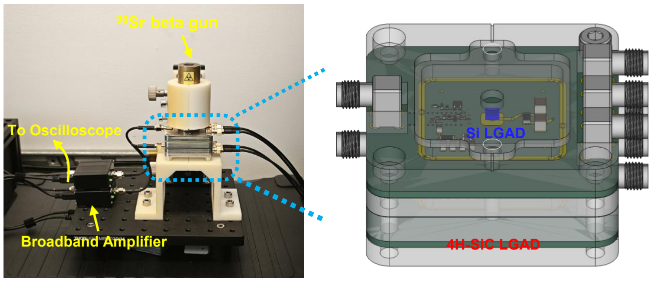

Fig. 3. Photograph of the ^{90}Sr source test setup. The Si LGAD was mounted on the upper circuit board, and the 4H-SiC LGAD was placed on the lower circuit board.

The device has a diameter of 300 μm and incorporates a field plate structure designed to effectively enhance the breakdown voltage [16]. The epitaxial structure consists of a (P^{++})–(N^{+})–(N^{-}) layer sequence: a 0.3 μm thick P^{++} contact layer with a doping concentration of $1 \times 10^{20}\ cm^{-3}$, a 0.5 μm thick N^{+} gain layer with a doping concentration of $4 \times 10^{17}\ cm^{-3}$, and a 75 μm thick N^{-} drift layer with a doping concentration of $\sim 2 \times 10^{14}\ cm^{-3}$. When a reverse bias of 500 V is applied, the gain layer forms a wedge-shaped electric field exceeding 3 MV/cm, enabling charge multiplication via impact ionization as carriers drift into this high-field region. This 4H-SiC LGAD achieves a gain of 7–8 which is measured by UV-TCT [16]. Fig. 2(a) shows the I–V characteristics measured in the initial state and after prolonged reverse bias stress (RBS) at room temperature. The SiC LGAD exhibited an initial breakdown voltage ($V_{\rm BD}$) of 520 V, which increased to 810 V after reverse bias stress and the leakage current remained below 40 nA prior to breakdown. The increase in breakdown voltage is attributed to the trapping of carriers by SiC/SiO_2 interface defects. The defects at the SiC/SiO_2 interface can trap carriers generated by avalanche multiplication or thermally emitted carriers during reverse bias stress (RBS), forming fixed charge centers. These trapped charges reduce the electric field peak at the termination, leading to an increase in the breakdown voltage [17]–[19]. The C–V curve in Fig. 2(b) exhibits a characteristic capacitance drop due to the multilayer doping structure of the LGAD, with the depletion voltage of the gain layer V_{GL} identified at approximately 100 V. The capacitance then drops sharply, and with further increase in voltage, the drift layer begins to deplete. The full depletion voltage V_{FD} is about 1050 V based on TCAD simulation. With the increase in depletion region thickness, the device collects more charge generated by MIP ionization, which then drifts toward the gain layer and undergoes avalanche multiplication to produce additional charge carriers. Since the breakdown voltage of the SiC LGAD is lower than its full depletion voltage, the device operates in a partially depleted state within the voltage range from 300 V to 650 V applied in this experiment, with the capacitance ranging from 0.4 pF to 1 pF.

III. Test Setup

To measure the time resolution of the 4H-SiC LGAD, a 50 μm thick, 1.3 $mm \times$1.3 mm Si LGAD with a gain of

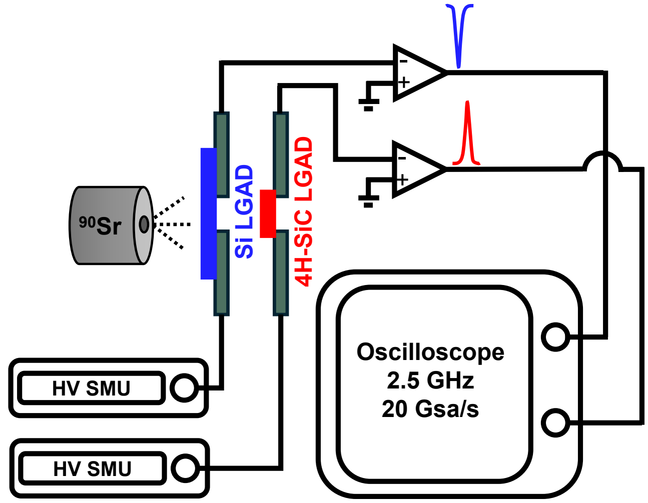

Fig. 4. Schematic of the ^{90}Sr source test setup.

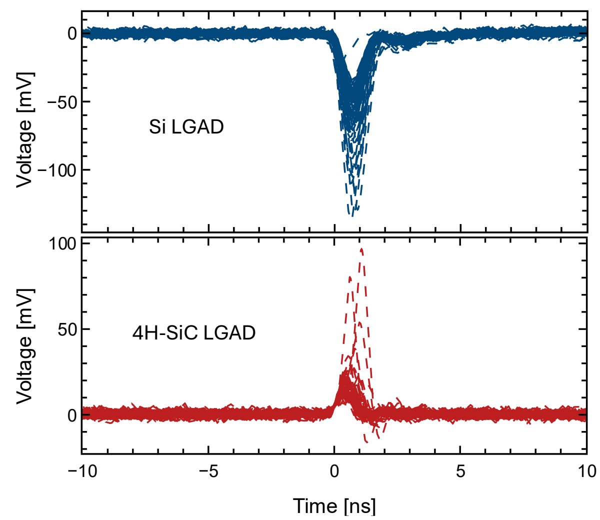

Fig. 5. Sampled waveforms with the ^{90}Sr source: (a) pulse signal detected by the Si LGAD; (b) pulse signal detected by the 4H-SiC LGAD.

10-20 from Brookhaven National Laboratory (BNL) [10] was used as the timing reference device in the ^{90}Sr source setup. The time resolution of the BNL Si LGAD has been previously determined using a ^{90}Sr source with a value about 41 ps. Fig. 3 shows the ^{90}Sr source test system. As illustrated in Fig. 4, two high-speed readout boards, each equipped with a 2 GHz bandwidth transimpedance amplifier (TIA), were stacked together. The front board was mounted with a Si LGAD, while the rear board housed the 4H-SiC LGAD. To minimize scattering and attenuation of the incident beta particles by the PCB, each board featured a 2 mm diameter through-hole at the center of the device mounting pad. The ^{90}Sr source emits a continuous beta spectrum with a maximum energy of 0.546 MeV from ^{90}Sr and a maximum energy of 2.28 MeV from ^{90}Y; a portion of the particles can penetrate both the Si LGAD and the 4H-SiC LGAD, inducing current pulses in each detector. These signals were amplified by the transimpedance amplifier followed by secondary broadband

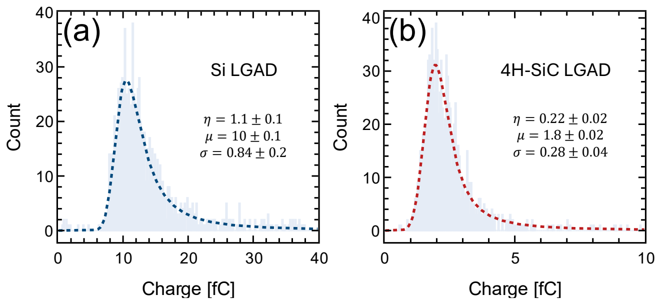

Fig. 6. Charge collection distribution of the ^{90}Sr source and Landau-Gaussian convolution fit results: (a) Si LGAD at 250 V; (b) 4H-SiC LGAD at 500 V.

amplifiers, and then captured by a high-speed oscilloscope. Since both the TIA on the readout board and the external wide-band amplifier are inverted, the polarity of the final output pulse signal remains unchanged. To calibrate the actual transimpedance of the TIA and enable an accurate measurement of the collected charge, two complementary methods were employed to calibrate the readout board: (i) charge injection through a calibration capacitor (0.3 pF), and (ii) measurement of the collected charge from β particles using a 300 μm thick ATLAS ITk silicon diode. Once the transimpedance Z of the TIA is calibrated, the relationship between the input current I_{in} and the output voltage is given by $V_{\text{out}} = I_{\text{in}} \times Z$. The collected charge can then be obtained by integrating the input current over time, $Q = \int I_{\text{in}}\, dt \propto \int V_{\text{out}}\, dt$.

Fig. 5 shows the signal pulses of the Si LGAD and the 4H-SiC LGAD captured by the oscilloscope. Since the Si LGAD is a P-in-N structure while the 4H-SiC LGAD is an N-in-P structure, their pulse polarities are opposite. Fig. 6 shows the collected charge distribution, where the most probable value (MPV) is extracted by fitting with a Landau distribution. Fig. 7 presents the collected charge as a function of bias voltage. Since the collected charge of the Si PIN and 4H-SiC PIN detectors without gain is below the equivalent noise level of the readout electronics in this experiment, the theoretical expectations are shown in Fig. 7. As mentioned in Sec. II, the 4H-SiC LGAD operates in a partially depleted state within the applied bias range of this experiment. For comparison, both the fully depleted and partially depleted charge collection ranges are illustrated in Fig. 7(b).

IV. Timing Performance

To measure the time resolution, the same method described in [6] was employed. Using the constant fraction discrimination (CFD) technique, the timing points at the same fraction of the pulse amplitude were extracted for both the Si LGAD and the 4H-SiC LGAD, denoted as t_{Si} and t_{SiC}, respectively. The time difference was then calculated as $\Delta T = t_{\text{SiC}} - t_{\text{Si}}$. The time spread $\sigma_{\Delta T}$ was extracted by performing a Gaussian fit to the distribution of ΔT. As shown in Fig. 8(a), $\sigma_{\Delta T}$ reaches its minimum for fractions between 30% and 50%. Fig. 8(b) shows the ΔT distribution and fitting result for a 40% fraction. In this work, a 40% fraction was consistently used to achieve the optimal time resolution. Since $\sigma^2_{\Delta T} = \sigma^2_{\text{Si}} + \sigma^2_{\text{SiC}}$, and the time resolution of the Si LGAD σ_{Si}, is known, the time resolution

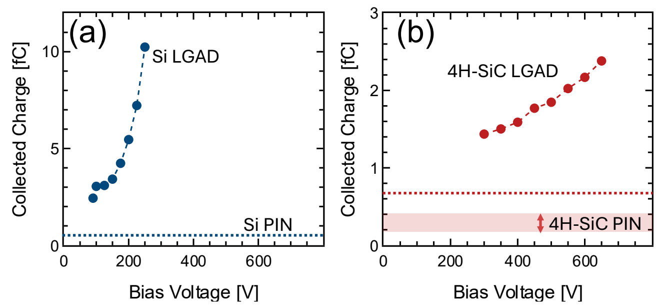

Fig. 7. (a) Collected charge of the Si LGAD as a function of bias voltage, with the dotted line indicating the theoretical generated charge for MIPs in a fully depleted Si PiN detector of the same thickness; (b) Collected charge of the 4H-SiC LGAD as a function of bias voltage, with the dotted line indicating the theoretical generated charge for MIPs in a fully depleted 4H-SiC PiN detector of the same thickness, and colored region shows the theoretical generated charge for MIPs in the operated voltage range.

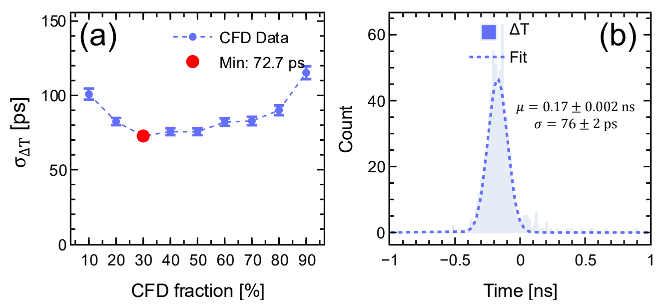

Fig. 8. 4H-SiC LGAD at a bias voltage of 500 V: (a) $\sigma_{\Delta T}$ obtained using a 10%–90% fraction; (b) ΔT distribution at a 40% fraction with Gaussian fit.

of the 4H-SiC LGAD σ_{SiC} can be extracted by deconvolving σ_{Si} from $\sigma_{\Delta T}$ in quadrature.

Fig. 9 shows the time resolution results measured by the ^{90}Sr source. The 4H-SiC LGAD achieves a time resolution of 61 ps when measured with beta particles from the ^{90}Sr source, which is comparable to that of conventional Si LGADs with ~50 ps [20] and better than that of 4H-SiC PiN with ~100 ps [5], [6]. It is also observed that the time resolution of the 4H-SiC LGAD measured with beta particles is worse than that of the Si LGAD. This is due to the smaller charge generated by beta particles in the 4H-SiC LGAD. However, compared with Si LGADs, the 4H-SiC LGAD developed in this work exhibits a smaller capacitance, and the faster carrier drift velocity at high bias voltage allows the device to achieve a time resolution of 61 ps. Compared with the 35 ps time resolution obtained previously using UV-TCT measurements at a fixed position [16], the degradation observed in the time resolution measured with β-source mainly originates from the time walk induced by the Landau distribution of the MIP energy deposition. In addition, the contribution arises from the time walk caused by the non-uniformity of the electric field within the device also results in a worse overall timing performance in the β source test.

Fig. 10 shows the measured time resolution as a function of collected charge. It confirms that beta particles produce significantly more charge in the Si LGAD than in the 4H-SiC LGAD, consistent with the charge distribution results shown

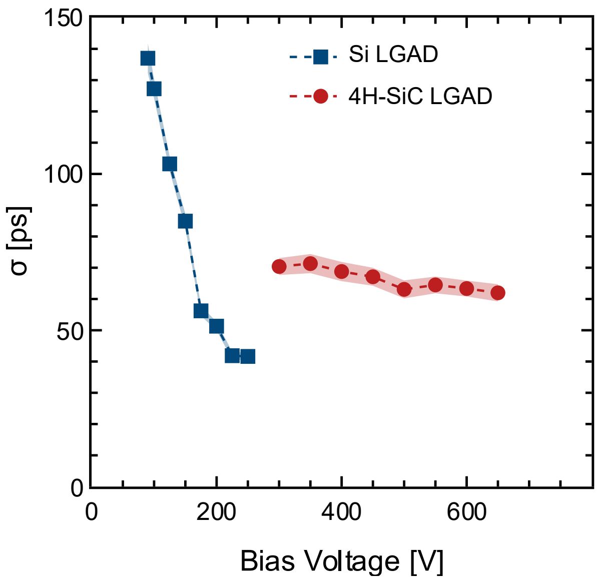

Fig. 9. Time resolution of the Si LGAD and 4H-SiC LGAD as a function of bias voltage.

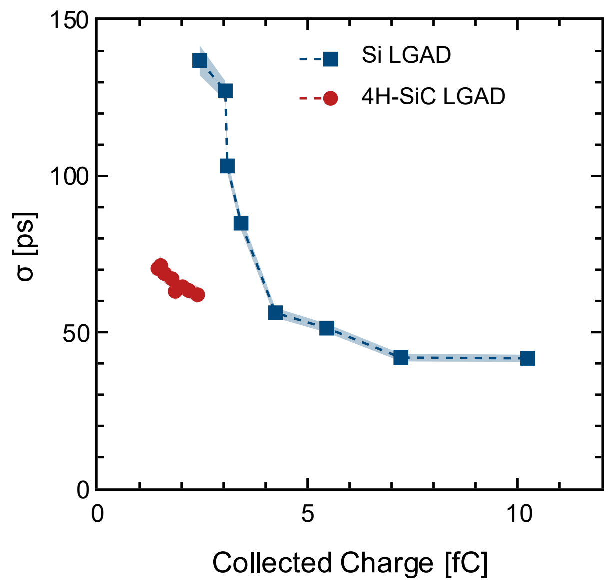

Fig. 10. Time resolution of the Si LGAD and 4H-SiC LGAD as a function of collected charges

in Fig. 6 and Fig. 7. These results indicate that the present limitation in the time resolution of 4H-SiC LGADs may be associated with the limited charge generation. Although the 4H-SiC LGAD studied in this work has a modest internal gain, the relatively high drift layer doping concentration and breakdown voltage hinder full depletion of the 4H-SiC LGAD under the available bias voltage, restricting charge generation. In addition, the intrinsically smaller charge yield of beta particles in 4H-SiC due to the lower ionization energy deposition further reduces the collected charge. Therefore, optimizing the device gain, as well as the thickness and doping concentration of the drift layer to increase charge collection, will be essential for future development of 4H-SiC LGADs. However, Fig. 10 also indicates that, for the 4H-SiC LGAD, even when the collected charge is small, the timing performance can be improved by increasing the bias voltage to enhance carrier drift velocity. Under the same collected charge, 4H-SiC LGADs benefit from smaller capacitance, higher voltage tolerance and faster carrier drift compared to Si LGADs. With higher charge collection, it is expected that the timing resolution could be further improved, potentially reaching or even surpassing that of Si LGADs.

V. Conclusion

In this work, the timing performance of recently developed 4H-SiC LGADs was evaluated using ^{90}Sr beta particles. The fabricated 4H-SiC LGADs exhibit fast response characteristics. Despite the relatively small collected charge under beta irradiation, time resolutions of 61 ps were achieved, demonstrating the potential of 4H-SiC LGADs for precision timing applications in high energy physics experiments. This result slightly outperforms the timing resolutions of SiC LGADs recently reported by other research groups under β source measurements [21].

Although the 4H-SiC LGAD studied in this work benefits from a smaller capacitance that supports faster signal formation, comparative studies with standard Si LGADs indicate that its time resolution is currently limited by the reduced signal charge, which results from the lower ionization energy deposition in SiC, the modest internal gain, and the partially depleted drift layer. Charge-dependent timing analysis further indicates that improving the collected charge is critical for enhancing time resolution. These results highlight the importance of further device optimization—particularly in terms of gain layer engineering and drift layer design—to maximize charge multiplication and collection.

Overall, this study provides the validation of 4H-SiC LGAD with good timing performance for MIPs detection, and lays the groundwork for potential applications in high-time-resolution detectors for 4D tracking in extreme environments such as next-generation colliders.

Acknowledgment

We gratefully acknowledge Gabriele Giacomini and Alessandro Tricoli from BNL for providing the Si LGAD samples and for their valuable assistance in device characterization.

References

[1] ECFA Detector R&D Roadmap Process Group, "The 2021 ECFA detector research and development road." doi: 10.17181/CERN.XDPL.W2EX.

[2] B. Fleming and I. Shipsey, "Basic research needs for high energy physics detector research & development." doi: 10.2172/1659761.

[3] S. Tudisco, C. Altana, S. Amaducci, C. Ciampi, G. Cosentino, S. De Luca, F. La Via, G. Lanzalone, A. Muoio, G. Pasquali, and A. Trifirò, "Silicon Carbide devices for radiation detection: A review of the main performances," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 1072, p. 170112, 2025. doi: 10.1016/j.nima.2024.170112.

[4] M. Christanell, M. Tomaschek, and T. Bergauer, "4H-silicon carbide as particle detector for high-intensity ion beams," *Journal of Instrumentation*, vol. 17, no. 01, p. C01060, 2022. doi: 10.1088/1748-0221/17/01/C01060.

[5] X. Zhang, J. W. Cates, J. P. Hayward, G. Bertuccio, D. Puglisi, and P. A. Hausladen, "Characterizing the Timing Performance of a Fast 4H-SiC Detector With an ^{241} Am Source," *IEEE Transactions on Nuclear Science*, vol. 60, 2013. doi:10.1109/TNS.2013.2260652.

[6] T. Yang, Y. Tan, Q. Liu, S. Xiao, K. Liu, J. Zhang, R. Kiuchi, M. Zhao, X. Zhang, C. Wang, B. Wu, J. Lin, W. Song, H. Lu, and X. Shi, "Time Resolution of the 4H-SiC PIN Detector," *Frontiers in Physics*, vol. 10, 2022. doi:10.3389/fphy.2022.718071.

[7] G. Pellegrini, P. Fernández-Martínez, M. Baselga, C. Fleta, D. Flores, V. Greco, S. Hidalgo, I. Mandić, G. Kramberger, D. Quirion, and M. Ullan, "Technology developments and first measurements of Low Gain Avalanche Detectors (LGAD) for high energy physics applications," *Nucl. Instrum. Methods A*, vol. 765, 2014. doi: 10.1016/j.nima.2014.06.008.

[8] H. F.-W. Sadrozinski, A. Seiden, and N. Cartiglia, "4D tracking with ultra-fast silicon detectors," *Rep. Prog. Phys.*, vol. 81, no. 2, 2018. doi: 10.1088/1361-6633/aa94d3.

[9] V. Sola, R. Arcidiacono, M. Boscardin, N. Cartiglia, G.-F. Dalla Betta, F. Ficorella, M. Ferrero, M. Mandurrino, L. Pancheri, G. Paternoster, and A. Staiano, "First FBK production of 50 um ultra-fast silicon detectors," *Nucl. Instrum. Methods A*, vol. 924, 2019. doi: 10.1016/j.nima.2018.07.060.

[10] G. Giacomini, W. Chen, F. Lanni, and A. Tricoli, "Development of a technology for the fabrication of Low-Gain Avalanche Diodes at BNL," *Nucl. Instrum. Methods A*, vol. 934, 2019. doi: 10.1016/j.nima.2019.04.073.

[11] K. Wu, M. Zhao, T. Yang, J. Guimarães da Costa, Z. Liang, and X. Shi, "Design of Low Gain Avalanche Detectors (LGAD) with 400 keV ion implantation energy for multiplication layer fabrication," *Nucl. Instrum. Methods A*, vol. 984, 2020. doi:10.1016/j.nima.2020.164558.

[12] Y. Fan, S. Alderweireldt, C. Agapopoulou, N. Atanov, M. K. Ayoub, D. Caforio, H. Chen, S. Christie, J. da Costa, H. Cui, G. d'Amen, Y. Davydov, R. Kiuchi, A. Ferreira, Z. Galloway, M. Garau, L. García, J. Ge, C. Gee, G. Giacomini, V. Gkoukousis, C. Grieco, S. Guindon, D. Han, S. Han, Y. Huang, Y. Jin, M. Jing, E. Kuwertz, C. Labitan, M. Leite, B. Li, H. Liang, Z. Liang, B. Liu, J. Liu, M. Lockerby, F. Lyu, N. Makovec, S. Mazza, F. Martinez-Mckinney, I. Nikolic, R. Padilla, B. Qi, K. Ran, H. Ren, C. Rizzi, E. Rossi, S. Sacerdoti, H.-W. Sadrozinski, G. Saito, B. Schumm, A. Seiden, L. Shan, L. Shi, Y. Tan, A. Tricoli, S. Trincaz-Duvoid, M. Wilder, K. Wu, W. Wyatt, X. Shi, T. Yang, Y. Yang, C. Yu, X. Zhang, L. Zhao, M. Zhao, Y. Zhao, Z. Zhao, X. Zheng, and X. Zhuang, "Radiation hardness of the low gain avalanche diodes developed by NDL and IHEP in China," *Nucl. Instrum. Methods A*, vol. 984, 2020. doi:10.1016/j.nima.2020.164608.

[13] P. Barletta, M. Cerullo, C. Haber, S. Holland, J. Muth, and B. Sekely, "Fast Timing With Silicon Carbide Low Gain Avalanche Detectors," 2022. arxiv: 2203.08554.

[14] T. Yang, C. Fu, W. Song, Y. Tan, S. Xiao, C. Wang, K. Liu, X. Zhang, and X. Shi, "Design and simulation of 4H-SiC low gain avalanche diode," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 1056, p. 168677, 2023. doi: 10.1016/j.nima.2023.168677.

[15] T. Yang, B. Sekely, Y. Satapathy, G. Allion, P. Barletta, C. Haber, S. Holland, J. F. Muth, S. Pavlidis, and S. Stucci, "Characterization of 4H-SiC Low Gain Avalanche Detectors (LGADs)," 2024. arxiv: 2408.12744.

[16] T. Yang, B. J. Sekely, Y. Satapathy, G. Allion, G. Atar, P. Barletta, C. Haber, S. Holland, J. F. Muth, S. Pavlidis, S. Stucci, and A. Tishelman-Charny, "Ultra-Fast 4H-SiC LGAD With Etched Termination and Field Plate," *IEEE Electron Device Letters*, vol. 46, no. 5, pp. 845–847, 2025. doi: 10.1109/LED.2025.3548509.

[17] S. Liu, C. Yang, W. Sun, Q. Qian, Y. Huang, X. Wu, M. Wu, Q. Yang, and L. Sun, "Repetitive-Avalanche-Induced Electrical Parameters Shift for 4H-SiC Junction Barrier Schottky Diode," *IEEE Transactions on Electron Devices*, vol. 62, no. 2, pp. 601–605, 2015. doi: 10.1109/TED.2014.2375821.

[18] F.-Y. Jin, P.-H. Chen, W.-C. Hung, W.-C. Hung, C.-H. Chang, F.-M. Ciou, Y.-S. Lin, K.-C. Chang, Y.-H. Lin, T.-T. Kuo, K.-H. Chen, C.-H. Yeh, and T.-C. Chang, "Analysis of Breakdown-Voltage Increase on SiC Junction Barrier Schottky Diode Under Negative Bias Stress," *IEEE Transactions on Electron Devices*, vol. 70, no. 1, pp. 191–195, 2023. doi: 10.1109/TED.2022.3223645.

[19] J. Li, T. Ding, L. Zhou, and Z. Wu, "Analysis of Effects of Defects on Degradation Mechanism of 1200-V/40-A 4H-SiC Junction Barrier Schottky Diodes Induced by High-Reserve Bias Stress," *IEEE Transactions on Electron Devices*, vol. 71, no. 5, pp. 2931–2935, 2024. doi: 10.1109/TED.2024.3379154.

[20] C. Agapopoulou, S. Alderweireldt, S. Ali, M. Ayoub, D. Benchekroun, L. Castillo García, Y. Chan, H. El Jarrari, A. Falou, A. Ferreira, E. Gkougkousis, C. Grieco, S. Grinstein, J. Große-Knetter, J. Guimarães da Costa, S. Guindon, A. Henriques Correia, S. Hidalgo, A. Howard, P. Hsu, Y. Huang, Y. Khoulaki, G. Kramberger, E. Kuwertz, J. Lange, C. Li, Q. Li, H. Lin, Y. Lu, N. Makovec, L. Masetti, R. Mazini, S. Mazza, I. Nikolic, G. Pellegrini, A. Quadt, B. Reynolds, C. Rizzi, M. Robles Manzano, A. Rummler, S. Sacerdoti, L. Serin, J. Soengen, Y. Tayalati, S. Terzo, E. Tolley, S. Trincaz-Duvoid, S. Wang, and X. Yang, "Performance in beam tests of irradiated Low Gain Avalanche Detectors for the ATLAS High Granularity Timing Detector," *Journal of Instrumentation*, vol. 17, no. 09, p. P09026, 2022. doi: 10.1088/1748-0221/17/09/P09026.

[21] P. Švihra, J. Chochol, V. Kafka, A. Klimsza, A. Kozelsky, J. Kroll, R. Malousek, M. Marčišovská, M. Marčišovský, M. Mikeštíková, M. Moll, D. Novák, R. Novotný, P. Slovák, R. Špetík, and M. Wiehe, "Exploring the design and measurements of next-generation 4H-SiC LGADs," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 1080, p. 170742, 2025. doi: 10.1016/j.nima.2025.170742.