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Silicon carbide sensors in radiotherapy dosimetry: progress, challenges, and perspectives

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Accurate dosimetry is crucial in radiotherapy and particle therapy to ensure that prescribed doses are delivered to tumors while minimizing damage to healthy tissue. Advanced dosimetry systems are needed to meet the challenges of modern techniques (small fields, high dose gradients, ultra-high dose rates). Silicon carbide (SiC), a wide bandgap semiconductor, has emerged as a promising material for next-generation radiation detectors. This review highlights the role of SiC in dosimetry for photon, electron, proton, and carbon ion beams, including the new FLASH ultra-high dose rate radiotherapy. We summarize SiC's advantageous physical properties and survey its use in various detector architectures. In conclusion, SiC shows excellent linearity, radiation tolerance, and the potential to complement or outperform conventional dosimeters. Ongoing developments and multidisciplinary research are expected to address remaining challenges and pave the way for SiC's integration into clinical dosimetry and future high-performance applications.

KEYWORDS
dosimetry, silicon carbide, radiotherapy, solid-state detector, particle therapy, ultra-high dose rate (UHDR), clinical application

1 Introduction

Accurate and reliable dosimetry is essential in modern radiotherapy to ensure precise delivery of prescribed doses to tumors while minimizing damage to healthy tissues. As treatment techniques become increasingly sophisticated-such as intensity-modulated radiation therapy (IMRT), volumetric modulated arc therapy (VMAT), stereotactic radiosurgery (SRS), proton therapy, and ultra-high dose rate (UHDR) FLASH radiotherapy-the requirements on dosimetric systems have also evolved. Dosimeters must now respond accurately across a wide range of dose rates, energies, and beam modalities, often with time-resolved (sub-microsecond) readout and high spatial fidelity. In practical terms, modern dosimeters must achieve: (i) time-resolved readout with sub-microsecond response for pulsed beams; (ii) wide dynamic range and linearity from conventional rates up to ultra-high dose-rate (UHDR) conditions; (iii) small active volume and high spatial resolution for small-field dosimetry; (iv) minimal energy dependence (near-water response) across kV–MV photon beams and clinical electron/proton energies; (v) robustness against cumulative dose and environmental drifts; and (vi) traceable calibration suitable for reference and end-to-end QA workflows. These requirements are emphasized by current recommendations and by recent commissioning studies in preclinical kV and FLASH contexts (Wolf et al., 2025;

Vignati et al., 2020; Andreo et al., 2024). In the specific case of FLASH radiotherapy, beams deliver > 40 Gy/s with total irradiation times < 200 ms and large dose-per-pulse values, imposing stringent constraints on detector time resolution (single-pulse capture), linearity at high dose per pulse (DPP), saturation avoidance, and robust calibration strategies. These conditions challenge standard protocols due to ion recombination, and they limit many commercial solid-state solutions; consequently, passive (films, alanine) and emerging active detectors (diamond, SiC) have been prominently investigated, alongside novel ionization chamber designs and compact calorimeters, to enable accurate Quality Assurance (QA) and beam monitoring in UHDR environments (Romano et al., 2022; Vignati et al., 2020; Petringa et al., 2025a). Traditionally, ionization chambers (ICs) serve as primary standards due to their accuracy, but their size and dose-rate limitations motivate the use of solid-state dosimeters for many clinical and research applications. At UHDR, standard ICs exhibit significant ion recombination and DPP-dependent saturation that require large, uncertain corrections, motivating alternative or adapted designs for accurate dosimetry under FLASH conditions. Recent developments have demonstrated ultrathin parallel-plate ICs and conceptual designs capable of sustaining UHDR without saturation, thereby extending the applicability of ICs to FLASH regimes (Di Martino et al., 2005; Gómez et al., 2022). Beyond ICs, standard non–solid-state dosimeters widely used in medical environments, also at UHDR, include radiochromic films and alanine, which are largely dose-rate independent but require offline readout and are thus sub-optimal for online QA and beam monitoring. Recently, compact graphite calorimeters have been explored for absolute dosimetry at UHDR. These constraints motivate the interest in active solid-state dosimeters that offer online, time-resolved readout while striving for reference-grade performance (Palmans et al., 2004; Di Martino et al., 2023; Bourgouin et al., 2022; Bass et al., 2022). Among the various dosimetric technologies available, solid-state detectors have gained considerable attention for their compactness, fast temporal response, and high sensitivity. Among active solid-state dosimeters, silicon diodes are long-established for relative and *in-vivo* dosimetry in conventional radiotherapy (photons/electrons), with numerous commercial arrays and point detectors routinely used in clinics; they provide high sensitivity and linear current-to-dose-rate response at conventional dose rates (Fleta et al., 2024; Jäger et al., 2021). Silicon-based detectors exhibit good charge collection efficiency and dose rate linearity at conventional dose rates (0.1–5 Gy/min), making them suitable for linac-based photon and (conventional-rate) electron therapy; however, under UHDR electron beams generated by dedicated linacs (e.g., ElectronFLASH), silicon diodes exhibit dose-per-pulse and instantaneous dose-rate limitations that require careful characterization or alternative designs (Aeffner et al., 2013; Jäger et al., 2021). Recent UHDR studies with silicon (and SiC) under FLASH electrons corroborate these constraints and design trade-offs (Okpuwe et al., 2024; Medina et al., 2024). Furthermore, their leakage current increases with dose, which is removed by baseline zeroing; however, dose-induced sensitivity (responsivity) drift may necessitate periodic recalibration. Another well-established material in radiation detection is diamond, particularly in the form of synthetic single-crystal or polycrystalline diamond detectors. Diamond boasts excellent tissue equivalence (effective atomic number $Z_{\text{eff}} \approx 6$), very low leakage current, and high radiation hardness (Verona et al., 2023, Verona et al., 2022; Ciancaglioni et al., 2012). Clinical dosimeters such as the PTW 60019 microDiamond are commercially available and offer high spatial resolution with minimal energy dependence (Laub and Crilly, 2014). However, the production cost of high-quality diamond remains high, and the availability of large-area detectors is limited. Moreover, polycrystalline variants can suffer from grain boundary effects, while single-crystal devices are delicate and require careful handling. Despite these limitations, diamond detectors have demonstrated reliable performance even under UHDR conditions and are currently among the most promising candidates for FLASH dosimetry (Kranzer et al., 2022; Angelou et al., 2024). In recent years, emerging materials have begun to attract interest for advanced radiation detection applications. Among them, metal halide perovskites, such as methylammonium lead iodide ($MAPbI_3$), have been proposed for their high charge carrier mobility, large stopping power, and solution-processable fabrication (Kakavelakis et al., 2020; Náfrádi et al., 2015). Perovskite detectors have shown high sensitivity to X-rays and gamma rays, with potential for large-area flexible dosimetry systems. Nevertheless, their application in radiotherapy is still limited due to instability under prolonged irradiation, humidity sensitivity, and the toxicity of lead-based compounds. Research is ongoing to improve their radiation hardness and environmental stability. Other novel materials under investigation include organic semiconductors (Posar et al., 2020), gallium nitride (GaN) (Pittet et al., 2015), gallium arsenide (GaAs) (Lioliou and Barnett, 2016), and amorphous selenium (a-Se) (Stavro et al., 2018). Organic semiconductors offer flexibility and ease of fabrication but typically suffer from low mobility and poor radiation resistance (Pearton et al., 2015; Sellin and Vaitkus, 2006). GaN and GaAs possess high breakdown fields and radiation tolerance, but their commercial availability in dosimetric form remains limited (Pearton et al., 2015; Sellin and Vaitkus, 2006). Amorphous selenium, historically used in medical imaging, has demonstrated promise in passive dosimetry applications, although its performance at high dose rates and its readout mechanisms are still under evaluation (Sellin and Vaitkus, 2006). In this context, silicon carbide (SiC) has emerged as a highly attractive candidate for next-generation dosimetry. SiC is a wide bandgap semiconductor (bandgap ~ 3.26 eV for 4H-SiC) with exceptional electronic, thermal, and mechanical properties. Its intrinsic low leakage current, high breakdown voltage, and strong resistance to radiation damage make it suitable for environments where conventional silicon detectors fail. SiC's partial carbon composition brings it closer to tissue equivalence compared to pure silicon, reducing over-response to low-energy photons. Moreover, its robustness under ultra-high dose rates, particularly in FLASH irradiation regimes, sets it apart from most other materials. SiC detectors were first explored decades ago, with initial radiation detection demonstrations in the 1960s (Ferber and Hamilton, 1966). However, only with advances in SiC epitaxial growth in the late 1990s, high-quality doping layers become available, enabling the fabrication of reliable SiC diodes for particle detection. The earliest studies targeting medical dosimetry appeared in the early 2000s. For example, Bruzzi et al. (2001) reported a preliminary characterization of SiC detectors under 22 MeV electrons and 6 MV photons, showing a linear

TABLE 1 Core physical properties of SiC vs. Si and diamond (focus materials for active clinical dosimetry). *Scope:* Table 1 intentionally focuses on Si/SiC/diamond as the most established active dosimetric semiconductors; other options cited in Intro are summarized qualitatively in Section 2.3.

Property	Diamond	Silicon	4H−SiC
Bandgap E_g (eV)	5.45	1.12	3.26
Electron-hole pair energy (eV)	13	3.62	7.78
Electron mobility (cm^2/Vs)	1,800–2,200	1,500	800–1,000
Thermal conductivity (W/cm· K)	20	1.5	3–5
Breakdown field (MV/cm)	~10	0.3	2.2–4.0
Displacement energy (eV/atom)	43	13–20	25
Z_{eff}	6	14	10
Thermal stability (qualitative)	Very high	Moderate	High

Data compiled primarily from Nava et al. (2008) for diamond, silicon and 4H-SiC baseline parameters; SiC device-level details and ranges consistent with Tudisco et al. (2018). Z_{eff} is the effective atomic number relevant to photon interactions.

charge response with dose up to at least 10 Gy (Bruzzi et al. 2001). This pioneering work established the feasibility of SiC-based dosimeters for radiotherapy applications. In subsequent years, many research groups continued to develop SiC dosimeters, culminating in dedicated *in-vivo* dosimetry prototypes by the 2010s (e.g. Bertuccio et al. (2014)). This review aims to provide an overview of the use of SiC in dosimetry for radiotherapy with photons, electrons and protons beams and in the emerging context of FLASH radiotherapy. We begin by examining the physical properties that make SiC a promising material for radiation detection. We then address the challenges faced by solid-state detectors, comparing the performance of SiC with that of silicon, diamond, and other emerging materials. Finally, future directions are proposed, with particular emphasis on the development of clinical-grade systems and novel applications.

2 Physical and technological properties

2.1 Material properties relevant to dosimetry

Silicon carbide's material properties make it highly attractive for radiation detection (Table 1). Leading among its distinguishing characteristics, is the wide bandgap energy E_g (3.2 eV for 4H-SiC), approximately three times greater than that of silicon (Nava et al., 2008). This wide bandgap results in an exceptionally low rate of thermally generated carriers, thereby minimizing leakage current even at ambient temperature, and permits reliable operation at elevated temperatures without significant degradation in performance (Guarrera et al., 2022, Guarrera et al., 2025a). The intrinsic carrier concentration of 4H-SiC is orders of magnitude lower than silicon's, contributing to SiC devices' excellent signal-to-noise ratio even after radiation exposure. SiC also has high carrier mobilities (electron mobility ~ 1000 cm^2/Vs in 4H-SiC) and saturation velocities, enabling fast charge collection. While SiC can sustain higher electric fields (≈ 3–4 MV cm^{-1}) than Si, routine dosimetric operation typically uses 0–50 V bias or even 0 V (e.g., commercial diamond, and recent SiC graphene-contact diodes), i.e., well below the Si breakdown regime. The practical relevance of SiC's high critical field is thus indirect: it enables fully-depleted thin epitaxial layers at modest bias, robustness to leakage/defect growth, and headroom for specialized time-resolved/UHDR readout when higher drift fields can improve charge-collection speed (Tudisco et al., 2018; Bruzzi et al., 2001; Lopez Paz et al., 2024). Additionally, SiC's thermal conductivity (3–5 W/cm· K) is second only to diamond's and an order of magnitude greater than silicon's. In current-mode readout the junction temperature impacts dark current and gain stability; higher thermal conductivity helps dissipate local heating, reducing output drift during long irradiations or inside confined phantoms. Under UHDR pulsed beams, improved heat flow mitigates transient thermal build-up in encapsulated dosimeters, supporting stable per-pulse waveforms (Tudisco et al., 2018; Okpuwe et al., 2024). Another important aspect is SiC's large displacement energy per atom (estimated ~ 25 eV in 4H-SiC) (Nava et al., 2008). This means that creating permanent lattice defects in SiC requires more energy transfer than in silicon (13–20 eV). In practical terms, under a given flux of high-energy particles, SiC will accumulate defects more slowly than silicon, endowing it with superior radiation tolerance. Moreover, the atomic composition of SiC (50% Si, 50% C) gives it an effective atomic number $Z_{eff} \approx 10$, closer to that of tissue ($Z_{eff} \approx 7.4$) than pure silicon (Z = 14). This implies a more tissue-equivalent response, reducing energy dependence in photon fields. In practical terms, Z_{eff} governs low-energy photoelectric over-response (kV), so materials nearer to water (diamond ≈ 6, SiC ≈ 10) need smaller energy-response corrections than silicon (14); in MV, Compton dominance makes Z_{eff} differences largely negligible.

In summary, SiC combines low leakage from its wide bandgap with high thermal conductivity, which together underpin stable operation at elevated temperatures and reduced thermal drift during prolonged irradiations, key advantages for dosimetry (Nava et al., 2008). These intrinsic properties underpin SiC's strong performance as an active dosimeter material. The following subsections illustrate how these material advantages translate into enhanced device performance for dosimetric applications.

2.2 Device architectures and readout modes

A variety of SiC device architectures have been employed for dosimetry. The simplest and most common structure is the planar

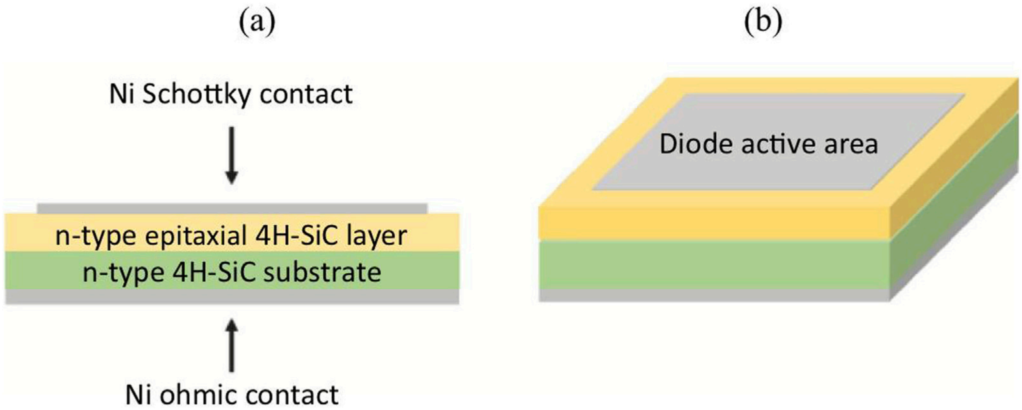

FIGURE 1
Schematic of the Schottky barrier diode **(a)** cross-section and **(b)** three-dimensional view.

Schottky diode: a rectifying metal contact on a doped SiC epitaxial layer with a conductive backside contact. Under reverse bias, a depleted sensitive volume forms in the semiconductor; electron–hole pairs generated by radiation are swept by the electric field and collected at the contacts. In Schottky diodes, the depletion region extends beneath the metal–semiconductor barrier, whereas in p–n diodes it spans the space-charge region across the junction. Schottky SiC diodes are relatively easy to fabricate and have been widely used in studies (e.g., for photon, electron, and proton beam dosimetry) (Bruzzi et al., 2001; Bertuccio et al., 2014; Lopez Paz et al., 2024; Capan, 2022; Fleta et al., 2024; Matsumoto et al., 2023). Figure 1 shows a typical Schottky SiC detector geometry (adapted from Capan (2022)).

p-n diodes in SiC have been explored, though forming shallow junctions in SiC can be technologically challenging due to its low dopant diffusion coefficients (La Via et al., 2014; Matsunami and Kimoto, 1997). One advantage of p-n diodes is the purely semiconductor interface (avoiding metal-semiconductor barrier in Schottky), potentially reducing leakage further, though SiC Schottky diodes already have extremely low dark currents. An important initiative to advance p-n junction SiC detectors was the SICILIA project (Silicon Carbide Detectors for Intense Luminosity Investigations and Applications), a collaboration between the Italian National Institute for Nuclear Physics (INFN) and the Institute for Microelectronics and Microsystems of the National Research Council (IMM-CNR), fully funded by INFN (Tudisco et al., 2018; Altana C. et al., 2023). The project targets high-quality homoepitaxial growth on low-defect-density 4H-SiC substrates to enable detector-grade layers with controlled thickness and doping, which are directly relevant to Schottky, p–n, MSM, and MOSFET dosimetric architectures. These process improvements—demonstrated within the SICILIA program—translate into lower leakage, higher breakdown fields and reproducible active thicknesses that are beneficial not only for nuclear-physics devices but also for radiotherapy dosimetry (Altana C. et al., 2023; Tudisco et al., 2018; La Via et al., 2014). In practice, 'defect-free' SiC at wafer scale is not realistic; the goal for detector-grade material is to minimize electrically active defects. State-of-the-art 4H-SiC uses CVD with optimized chlorinated chemistry (e.g., trichlorosilane + HCl) and high growth rates to suppress homogeneous Si nucleation, reduce basal-plane dislocations and Shockley stacking faults, and improve lifetime uniformity across the wafer, which directly benefits leakage and breakdown margins. Leakage minimization relies on defect-minimized epitaxy, high-quality surface passivation and multi-guard-ring edges to suppress perimetral currents; clean metal stacks and controlled anneals limit interface states. Combined with the wide bandgap, these measures yield ultra-low dark currents at room temperature and stable breakdown margins over the radiotherapy temperature range, enabling low-noise current-mode or pulse-mode dosimetry. As illustrated in Figure 2, one device features a thin p^+ layer on a lightly doped n epitaxial layer, an architecture optimized for efficient charge collection and radiation tolerance.

Metal–semiconductor–metal (MSM) photodiodes employ two back-to-back Schottky contacts patterned as interdigitated fingers on a semi-insulating or lightly doped SiC layer. Unlike Schottky or p–n diodes with a vertical depletion region, MSMs establish a predominantly lateral drift region between adjacent fingers; the sensitive volume and response time are governed by finger spacing, depletion width under each contact, and carrier transport in the intervening gap. MSM detectors are known for their fast temporal response and ease of fabrication (Zhang, 2015; Sellin and Vaitkus, 2006). However, their sensitive volume is generally smaller than in Schottky or p-n diodes, limited by the spacing of electrodes and the resistivity of the substrate. A typical structure is shown in Figure 3, where the MSM photodetector is fabricated on an n-type 4H-SiC epilayer over a heavily doped n^+ 4H-SiC substrate with Au/Ni Schottky contacts and passivation layers of SiO_2 and Al_2O_3 Zhang (2015). SiC MOSFET dosimeters infer dose or dose rate from radiation-induced shifts in threshold voltage or from changes in transistor current, analogous to silicon MOSFET dosimeters used clinically. Thanks to SiC's radiation hardness, the devices show reduced drifts at high total dose; however, threshold shifts in SiC are typically smaller than in silicon and demand low-noise, high-resolution readout. A representative n-channel 4H-SiC structure comprises a lightly doped epilayer on a SiC substrate, heavily doped source/drain regions, and a SiO2 gate dielectric (Yadav et al., 2016).

While a broad MSM/MOSFET literature exists for UV photodetection and power electronics, reports focused specifically on radiotherapy dosimetry are comparatively few; we therefore show

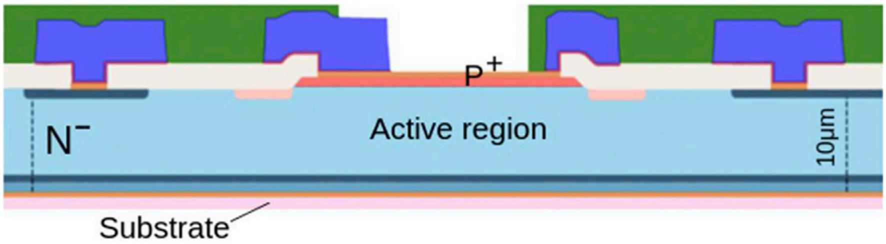

FIGURE 2
Schematic cross-section of a SiC p-n diode with a 10 μm-thick n^- epitaxial layer grown on a 350 μm-thick substrate.

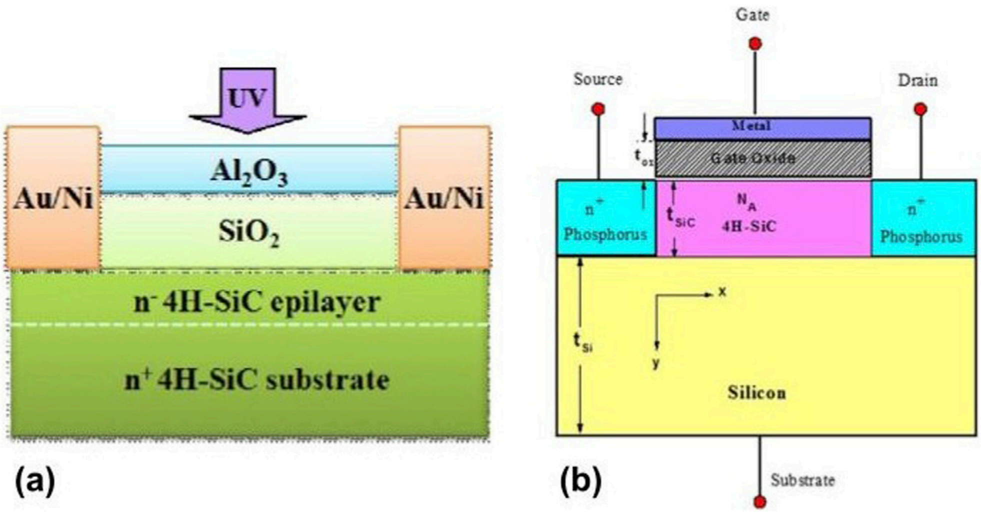

FIGURE 3
(a) A cross-sectional view of 4H-SiC MSM photodetectors Zhang (2015) **(b)** Cross-section of a SiC MOSFET dosimeter Yadav et al. (2016).

representative implementations. Regardless of device structure, the readout modes for SiC detectors can be categorized as:

1. Current mode: the detector is biased and the steady-state current (pA–nA range) induced by a radiation beam is measured, usually with a low-noise ammeter or integrator. This mode provides real-time dose rate information and is commonly used for continuous beams (e.g., clinical linac output at nominal dose rates). In practice, integrating the measured current over irradiation time yields the collected charge, which, after calibration, provides the absorbed dose, as routinely done also for conventional linacs.
2. Pulse mode resolves the charge associated with each radiation pulse (or single particle), using a charge-sensitive preamplifier and shaping electronics. For high-repetition beams, summing pulse-by-pulse charge converges to the same average as current mode, but pulse mode preserves per-pulse information (e.g., dose-per-pulse and instantaneous dose rate), which is critical for UHDR/FLASH characterizations.

The mode chosen depends on the application requirements: current mode is simpler and often sufficiently linear, while pulse mode may better handle extreme dose rates. Recent studies have demonstrated robust linearity and stable response of SiC diodes at ultra-high dose-per-pulse when read in pulse-resolved configurations, supporting their use in FLASH beams (Fleta et al., 2024; López Paz C. et al., 2025). To protect SiC diodes from electrostatic discharge and sudden voltage spikes, simple, well-established measures are adopted at the detector and readout level. The preamplifier input is protected with small, fast surge-protection diodes and a modest series resistor to limit fault current. The bias line includes a resistor–capacitor filter to smooth abrupt transients. The detector layout uses multiple guard rings and high-quality edge passivation to suppress surface currents. Cables and connectors are shielded, and the system is assembled and handled under standard electrostatic-control procedures. Together, these measures prevent damage without reducing the ability to record very short radiation pulses. In the remainder, Sections 3–5 concentrate on Schottky and p–n diodes, the architectures most mature for clinical dosimetry, while MSM and MOSFET devices are highlighted where dosimetric results are available (e.g., time response and stability in pulsed/UHDR beams).

TABLE 2 Comparison of selected detector materials commonly used in radiotherapy dosimetry.

Characteristic	4H-SiC	Silicon (Si)	Single-crystal diamond
W-value/Sensitivity per unit colume (pC/mGy $\cdot mm^3$)	≈425	≈644	≈259
Bandgap and leakage/noise (qual.)	Wide bandgap; very low leakage and low noise	Narrow bandgap; higher dark current/ noise	Wide bandgap; ultra-low leakage and noise
Energy dependence at kV (qual.)	Intermediate tissue-equivalence; energy dependence mitigated by thin/metal-light contacts	Stronger over-response vs. tissue; highly sensitive to entrance window	Most tissue-equivalent; mild energy dependence; entrance window still relevant
UHDR linearity (per-pulse/DPP)	Linear up to very high DPP; response largely independent of DPP within a few percent	Limited evidence; device-specific behavior	Demonstrated UHDR linearity in literature (device-dependent)
Accumulated-dose effects (sensitivity drift)	Small sensitivity change ($\approx 1-2\%$ scale at $\approx 10^2$ kGy, beam- and device-dependent)	Noticeable drift with high total doses; depends on beam/energy and device	Good long-term stability; small drifts reported at high doses
Operation at 0 V/bias note	Operation at 0 V demonstrated; also robust under reverse bias	Typically requires bias for diode operation	Can operate at low/zero bias in specific designs

2.3 Comparison across detector materials used in radiotherapy dosimetry

SiC diode dosimeters offer a distinctive combination of radiation tolerance, real-time readout, and long-term stability when compared with established detector materials, notably silicon and single-crystal diamond. To keep the comparison physically meaningful, we separate material properties (e.g., Z_{eff}, bandgap, W-value) from device-level factors (active area, entrance window, readout), since the latter ultimately set spatial resolution and part of the energy response; in particular, spatial resolution is geometry-driven and thus not used here to discriminate across materials. Table 2 summarizes key properties and typical behaviours for Si, diamond, and 4H-SiC.

A quantitative baseline for charge sensitivity per unit volume is provided in Fleta et al. (2024), Table 1: Si ~644, diamond ~259, and 4H-SiC ~425 pC/(mGy·mm^3), which consistently explains the relative signal levels observed for similarly biased diode dosimeters. Owing to their wide bandgap, diamond and SiC exhibit markedly reduced dark currents compared to silicon, enabling lower-noise readout in dosimetry configurations (Bertuccio et al., 2014; Fleta et al., 2024). At kilovoltage photon energies, tissue-equivalence and entrance-window design dominate the response: diamond ($Z_{\mathrm{eff}} \approx 6$) is closest to soft tissue, SiC ($Z_{\mathrm{eff}} \approx 9$–$10$) is intermediate, and Si ($Z = 14$) tends to over-respond unless the entrance region is carefully engineered; metal-light solutions such as graphene contacts mitigate low-energy perturbations by reducing metal over the active area (Lopez Paz et al., 2024). Regarding ultra-high dose-per-pulse (UHDR) performance, 4H-SiC diodes have demonstrated per-pulse linearity and independence from DPP/instantaneous dose rate up to ~11 Gy/pulse at the Physikalisch–Technische Bundesanstalt (PTB, Germany) UHDR reference electron beam (Fleta et al., 2024) (see also Bourgouin et al. (2022) and beyond 10 Gy/pulse on ElectronFLASH (Milluzzo et al., 2024), with earlier campaigns reporting percent-level deviations (Romano et al., 2023); these statements refer to *per-pulse/per-field* linearity during a measurement session. Beyond per-pulse linearity, long-term behaviour under accumulated dose is considered separately. In electron beams, SiC diodes typically exhibit small sensitivity changes whose magnitude depends on beam and device details; representative measurements report <2% at 100 kGy with 20 MeV electrons (Fleta et al., 2024) and ± 0.75% at 90 kGy with 9 MeV UHDR electrons on ElectronFLASH (Romano et al., 2023). Under conventional proton beams (83–220 MeV), SiC devices maintain a stable response with pA-level dark currents and linearity across clinically relevant dose-rate ranges; operation at 0 V has also been demonstrated when geometry permits (Bruzzi and Verroi, 2023). Comparable UHDR suitability has been documented for single-crystal diamond, Kranzer et al., 2022), which also benefits from near-tissue equivalence at kV energies and very low leakage; however, availability and cost considerations can be more constraining than for Si or SiC in routine deployments (Ciancaglioni et al., 2012; Laub and Crilly, 2014; Angelou et al., 2024). In contrast, silicon diodes, while mature and widely available, are more sensitive to dose-history and beam-quality effects across different radiation fields, generally requiring tighter control of calibration and corrections in demanding conditions (Rafí et al., 2020; Lopez Paz I. et al., 2025; Altana et al., 2023a). Finally, we emphasise that the quantitative examples reported here are *illustrative* and not material limits: radiation-damage trends depend on particle species, energy spectrum and fluence, as well as on entrance window/contact and active thickness (see also the broader discussions in Fleta et al., 2024; Jiménez-Ramos et al., 2025; Rafí et al., 2020; Lopez Paz C. et al., 2025; Altana et al., 2023a). Overall, Table 2 focuses on (i) the material constants that govern kV-energy dependence and noise floor, and (ii) representative device-level behaviours under UHDR and high cumulative dose; by design, non-discriminative items such as "real-time readout" and "spatial resolution", the latter being geometry-driven, are not used as comparison criteria.

3 Photon and electron radiotherapy

Megavoltage photon beams, ranging from a few MV to 25 MV, and electron beams, spanning 4–25 MeV, are primarily produced by medical linear accelerators (linacs) for use in external beam radiotherapy. These well-established methods rely on precise dosimetry protocols to ensure both the safety and effectiveness of treatments. Reference dosimetry is generally performed using ionization chambers, following the IAEA TRS-398 code of practice (Andreo et al., 2024). For relative and *in-vivo* measurements, clinical guidelines require that relative dosimetry detectors (diodes) demonstrate short-term reproducibility better than 0.5%, long-term stability within ± 0.5% over 2 weeks (International Atomic Energy Agency, 2013). In addition, preferred characteristics include high sensitivity, low leakage current (typically < 1% over 1 h), weak dependence on dose rate (within 0.5%), minimal angular and energy dependence, and negligible temperature sensitivity. While silicon and diamond detectors are well characterized and widely used for relative dosimetry, research into SiC remains active. The following subsection discusses selected studies on the performance of SiC detectors under clinical irradiation conditions and does not represent an exhaustive review of all published work on this topic.

3.1 Performance of SiC detectors under clinical beams

SiC diodes have recently emerged as promising candidates for dosimetry in both photon and electron therapy owing to their wide bandgap, high radiation hardness, and low leakage current. Under a 6 MV photon beam, Bertuccio el al. focused on the evaluation of the SiC diode as a dosimeter (Bertuccio et al., 2014). The 4H-SiC semiconductor with an area of 5 mm^2 and a thickness of 8.6 μm was irradiated with a 6 MV photon beam and its sensitivity was compared with the commercially available Si dosimeters (SUN Nuclear, IBA, PTW). Since the thickness and area of each dosimeter are varying, the sensitivity was recalculated into the normalized sensitivity ($nC/cGy/mm^2$). As a result, the SiC, Si detectors from SUN Nuclear, IBA and PTW demonstrated 5.37E2, 1.64E3, 1.64E2, and 3.88E3 $nC/(Gy \cdot mm^3)$, respectively. After normalization by detector area, the SiC device demonstrated a sensitivity of the same order of magnitude as the commercial silicon diodes, indicating that SiC materials can provide a clinically useful charge yield and signal-to-noise ratio. Furthermore, the SiC detector exhibited a time stability of 0.6%, well within the recommended clinical limits, and negligible leakage current over a temperature range of 20–40 °C—characteristics that are crucial for *in vivo* dosimetry.

The performance of SiC detectors has also been evaluated using a ^{60}Co gamma source. Key parameters such as stability, reproducibility, signal-to-noise ratio, dose linearity, and dose-rate linearity were investigated. At a dose rate of 30.8 cGy/min, on–off beam cycling was employed to measure the current from an unbiased device. The measurements demonstrated high stability and reproducibility, along with a very low leakage current (≈ 0.3 pA). By integrating the measured current over time, a dose sensitivity of $3.3E2\,nC/(Gy \cdot mm^3)$ was obtained for the unbiased detector. The dose-rate dependence of the detector sensitivity, for a device volume of $0.0415\,mm^3$, was further assessed in the range of 0.2–0.3 Gy/min under applied bias voltages from 0 to 100 V. The results confirmed a linear relationship between dose rate and collected charge, yielding sensitivities of 13.73 nC/Gy and 24.53 nC/Gy at 0 and 100 V bias, respectively (Bruzzi et al., 2002).

More recently, López Paz et al. introduced and demonstrated the viability of a novel SiC prototype diode enhanced with an epitaxially-grown graphene layer. This innovative device represents a significant advancement in the design of semiconductor-based dosimeters, as the substitution of the conventional metal contact with graphene minimizes secondary interactions such as X-ray scattering, which can otherwise affect dose measurements, an especially critical factor in clinical environments where high precision is essential. The prototype was characterized under clinical conditions using a 6 MV photon beam with dose rates ranging from 1 to 6 Gy/min. The main focus of the evaluation was on the linearity of the current response as a function of the dose rate. The results demonstrated outstanding linearity across the entire dose-rate interval, with deviations consistently remaining below 1%, confirming the device's reliability and stability. The integration of graphene not only preserves the electrical performance of the detector but also enhances its tissue equivalence and reduces perturbation effects (Lopez Paz et al., 2024).

Comparable study has been conducted under electron beam over clinically relevant dose ranges $(1-10\ Gy)$ and dose rates $(2-7\ Gy/min)$ to measure the response of SiC detectors with an active volume of 0.06 mm^3. At 4.2 Gy/min and under a reverse bias of 150 V, a linear correlation was observed between the collected charge and the absorbed dose, with a relative deviation of less than 2% and sensitivity 273 $nC/Gy \cdot mm^3$ (Bruzzi et al., 2001).

Although absolute sensitivity values (e.g., $nC/(Gy \cdot mm^3)$ depend strongly on detector geometry, the reported reproducibility, linearity, and low leakage currents of SiC detectors are within or close to the performance tolerances recommended for clinical dosimetry systems. For reference, commercial detectors such as the PTW microSilicon X (6.3E2 $nC/(Gy \cdot mm^3)$) and microDiamond (2.5E2 $nC/(Gy \cdot mm^3)$) exhibit sensitivities of the same order of magnitude as the SiC prototypes reported, confirming that SiC devices could operate within a clinically practical range with further optimization of geometry and calibration.

4 Proton and carbon ion therapy

Proton and carbon ion therapy are types of radiotherapy using charged particles in the range of 50–250 MeV for protons and 85–430 MeV per nucleon for carbon ion (Andreo et al., 2024). Unlike conventional photon therapy, charged particle beams offer a distinct depth-dose distribution with a sharp dose peak known as the Bragg peak. This feature allows precise tumor targeting and minimizing damage to surrounding tissue. However, the peculiarity of dose deposition imposes stringent dosimetric requirements in terms of spatial resolution, LET-dependence, etc. For clinical quality assurance, detectors are expected to provide sub-2% dose uncertainty, spatial resolution below 1 mm, and stable response over dose, dose rates ranging from 0.1 to 5 Gy/s. The typical range accuracy required for treatment planning verification is within 1 mm of the prescribed depth. In addition to these requirements, preferred detector characteristics include short- and long-term stability and reproducibility, high sensitivity, low leakage current, radiation hardness, linear response with respect to dose and dose rate, and negligible temperature dependence. In accordance with the IAEA technical report 398 (Andreo et al., 2024), the relative standard uncertainty of the absorbed dose at the reference depth, measured by a calibrated ionization chamber, should not exceed 1.7% for proton and 2.7% for carbon beams. However, there is growing interest in employing different solid-state detectors as alternative relative dosimeters. This is due to the higher ionization density in the semiconductor materials, which reduces the detector volume and, therefore, increases the spatial resolution. However, the higher ionization density, especially in high linear energy transfer (LET) beams such as the carbon beam, as well as at the distal edge of the Bragg peak, contributes to the saturation effect, requiring careful consideration in dosimetric applications. Unlike conventional radiotherapy, the use of semiconductor detectors for proton and carbon therapy has not yet been established clinically. For this reason, their application to relative dosimetry is currently under investigation and typically relies on cross-calibration against ionization chambers. One such semiconductor detector is SiC, which has been studied in the context of the detector response dependence on various factors and its possible use as relative dosimetry in proton and carbon ion therapy. The following subsections discuss the selected studies on the SiC performance irradiated by proton and carbon ions, and it does not represent a comprehensive review.

4.1 Performance of SiC detectors in proton therapy

Petringa et al. tested a SiC detector developed within the SICILIA project using clinical proton beams at 62 MeV, both monochromatic and modulated (Petringa et al., 2020). The detector exhibited excellent linearity across a dose range of 2–15 Gy, with deviations from the linear fit below 0.1%. Reproducibility was also high, with short-term variation (10 min) below 1% and long-term variation (6 months) remaining below 3%. While high sensitivity (in the order of a few nC/Gy) was observed, it should be noted that the device's larger active volume compared to conventional silicon diodes contributes to this enhanced charge collection. The main advantage lies not in the absolute sensitivity but in the demonstrated stability and linearity, which meet the clinical requirements for relative dosimetry.

Further studies were carried out by Bruzzi et al., who investigated the performance of a 4H-SiC detector as a real-time dosimeter for proton beams in the energy range of 83–220 MeV and extraction currents from 1 to 10 nA (Bruzzi and Verroi, 2023). The detector demonstrated excellent linearity in response to dose rates ranging from 5 mGy/s to 2.7 Gy/s. At zero bias, a sensitivity of 2.65 nC/Gy was observed, consistent with theoretical predictions. The device response was nearly linear with proton fluxes from 4.5×10^4 to 5.28×10^7 p/s, with deviations at fluxes below 10^5 p/s attributed to beam-detector geometry mismatches.

Recent developments include PRAGUE (Proton Range Measure using Silicon Carbide), a multilayer system composed of stacked thin SiC detectors (10 μm thick, 15×15 mm^2 area), designed to operate in both conventional and extremely high dose rate proton beams. Its configuration enables real-time acquisition of range and energy information with minimal signal recombination, high radiation hardness, fast response times, and low leakage current, providing accurate online proton spectrum reconstruction via a deconvolution procedure (Petringa et al., 2022).

4.2 Performance of SiC detectors in carbon therapy

A monoenergetic 290 MeV/u carbon beam at a maximum flux of therapeutic intensity (1E9 particles per second) was used to evaluate the response of SiC detectors in terms of radiation-induced current (RIC) under both biased and unbiased conditions at various depths in water (Kubodera et al., 2023). The RIC distribution reconstructed using the biased SiC detector was compared to the reference dose curve obtained from an ionization chamber along the Bragg peak. The peak-to-plateau ratios were found to be 3.68 for the SiC detector and 4.94 for the ionization chamber. Notable differences were observed in the plateau and tail regions, which were attributed to the SiC detector's sensitivity to fragment ions. In contrast, measurements using the unbiased SiC detector were conducted at fewer depth points but still compared to the ionization chamber results. Interestingly, the peak-to-plateau ratio recorded with the unbiased SiC detector was higher than that obtained under biased conditions, which could be explained by the underestimation of the RIC at the plateau. The authors of the work suggested that these discrepancies were likely due to limitations in the detector structure and configuration, indicating a need for further optimization.

Carbon ion beam features superior biological effectiveness due to the higher LET, while the study of the LET effect requires a detector with a high spatial resolution. As noted earlier, due to the ionization density and therefore the thickness of an active volume, SiC detectors are suitable for LET measurement. Utilizing this characteristic of the SiC detector, several studies have been performed. One such study was performed by Matsumoto et al., which investigated an energy-dispersive SiC dosimeter for measuring the LET distribution under irradiation with both pristine and spread-out Bragg peak (SOBP) carbon beams (Matsumoto et al., 2023). LET measurements were conducted using a 290 MeV/u carbon beam at multiple positions, including the plateau, SOBP, and post-Bragg peak regions. The measured and dose-averaged LET values were subsequently applied to estimate the relative biological effectiveness (RBE) using a linear-quadratic model, assuming a cell survival rate of 10%. The study showed the potential of SiC detectors to support clinical dose estimation in carbon ion therapy, although further validation is required.

4.3 SiC detectors for microdosimetry applications

In addition to macroscopic dose and LET measurements, SiC detectors are being investigated for microdosimetry, which quantifies stochastic energy deposition within micrometer-sized sensitive volumes relevant to biological effects.

Despite their advantages for microdosimetric studies—including high radiation hardness, fast response, low leakage currents, small active volumes, and high spatial resolution—SiC detectors have, to the best of our knowledge, not

TABLE 3 Comparison of typical irradiation parameters between CONV and FLASH radiotherapy (Vozenin et al., 2022). DPP is the dose per pulse; $D = n \cdot DPP$ is the total dose, where n is the number of pulses in the treatment; T is the delivery time; D/T is the mean dose rate.

Mode	DPP	D	T	D/T
CONV	~ mGy	2–8 Gy/fraction	>1 min	~ 1 Gy/min
FLASH	>1 Gy	>8 Gy/fraction	<200 ms	>40 Gy/s

yet been reported in full peer-reviewed publications for clinical or experimental use, except for a conference abstract (Petringa et al., 2025b), where measured spectra showed depth-dependent trends consistent with expected LET variations, and derived microdosimetric parameters agreed with reference detectors and simulations.

5 FLASH radiotherapy

Ultra-high dose rate radiotherapy (UHDR-RT), commonly referred to as FLASH radiotherapy, represents a novel and rapidly developing approach in radiation therapy. It is characterized by mean dose rates typically exceeding ~ 40 Gy/s, which are several orders of magnitude higher than those employed in conventional (CONV) clinical radiotherapy. Table 3 summarises the main parameters distinguishing CONV and FLASH irradiation modalities. While electron-based FLASH beams are presently best suited for superficial targets due to their limited range in tissue, depth-of-treatment can be addressed by alternative UHDR modalities. In particular, proton-FLASH and very-high-energy electrons (VHEE) are under active development to extend FLASH to deep-seated sites, whereas MV photon implementations are being explored in preclinical settings. From a dosimetric perspective, these modalities require accurate, time-resolved monitoring of dose-per-pulse, pulse width and instantaneous dose rate, for which fast solid-state sensors such as SiC have shown dose-rate-independent response and pulse-shape tracking capabilities.

This technique has gained growing attention following the observation of the so-called *FLASH effect*, a remarkable biological phenomenon in which normal tissues exhibit a significant reduction in radiation-induced toxicity, while tumor control efficacy remains comparable to that achieved with conventional dose rates (Favaudon et al., 2014; Gao et al., 2022; Adrian et al., 2023). This differential response effectively widens the therapeutic window, with reported reductions in the normal tissue complication probability (NTCP) ranging from 10% to 50%, while maintaining a dose-rate-independent tumor control probability (TCP) (Vozenin et al., 2022). Although the underlying mechanisms of the FLASH effect are still under active investigation, several hypotheses have been proposed (El Khatib et al., 2022; Guo et al., 2024). The magnitude of the FLASH sparing effect is expected to be tissue-dependent. Baseline oxygenation, vascularization and repair dynamics differ across organs and tumour histologies; consequently, the optimal combination of dose-per-pulse, pulse repetition frequency and total irradiation time may vary by tissue. Current evidence and mechanistic hypotheses (e.g., oxygen depletion kinetics) support including tissue-specific endpoints in protocol optimization and reporting FLASH-relevant beam parameters alongside biological outcomes. Ongoing preclinical studies continue to explore these mechanisms across various biological models and radiation modalities (Durante et al., 2017; Lin et al., 2021; Borghini et al., 2024). A complete, organ-specific optimization framework lies beyond the scope of this review; in practice, centres combine tissue-specific normal-tissue endpoints with systematic reporting of time-structure metrics (dose-per-pulse, pulse width, PRF, total delivery time) and validate safe operating windows using fast detectors (e.g., SiC) cross-checked against reference dosimetry. The first evidence of clinical feasibility was reported in 2019, when a 75-year-old patient with skin lymphoma received a single 15 Gy fraction in 90 ms using a 5.4 MeV electron beam, marking the first human FLASH treatment (Bourhis et al., 2019). More recently, the first proton FLASH clinical trial demonstrated the potential to extend the technique beyond electron-based systems, confirming the clinical viability of FLASH-RT using particle beams (Mascia et al., 2023). To safely and reproducibly deliver UHDR-RT, the development of advanced dosimetric systems is of paramount importance. Accurate, real-time, and high-resolution measurements are required to monitor beam output and spatial uniformity under such extreme irradiation conditions. However, conventional dosimeters, optimized for standard dose-rate applications, often exhibit saturation effects, non-linear response, or significant recombination losses when exposed to UHDR pulses. Therefore, the design and characterization of radiation-hard, fast-response detectors are crucial steps toward establishing reliable dosimetric protocols and robust quality assurance frameworks for the clinical implementation of FLASH radiotherapy (Montay-Gruel et al., 2023). In this context, SiC detectors have emerged as promising candidates due to their fast response time, high radiation tolerance, and potential for real-time operation. Recent investigations have demonstrated the capability of SiC devices to maintain stable operation and a linear dose response under both UHDR electron and proton beams. Radiation hardness studies confirmed that SiC devices exhibit leakage currents up to four orders of magnitude lower than their silicon counterparts, maintaining rectifying behaviour even after irradiation fluences exceeding 10^{15} cm^{-2} (Rafí et al., 2020). Similarly, Altana et al. highlighted the superior radiation tolerance of SiC devices, reporting stable charge collection efficiency and leakage current after heavy-ion exposure, outperforming silicon devices by more than two orders of magnitude (Altana et al., 2023b). Romano et al. developed a 10 μm-thick SiC detector specifically optimized for real-time absolute and relative dosimetry under UHDR conditions. The device exhibited a linear response up to 2 Gy per pulse (2 μs pulse duration), with only mild saturation beyond this range, and maintained a stable response within $\pm$ 0.75% after cumulative exposures up to 90 kGy (Romano et al., 2023). To mitigate saturation effects at higher doses per pulse, Milluzzo et al. proposed an upgraded readout architecture coupling the detector to an optimized external circuit. The improved configuration extended the linear range up to 5 Gy per pulse and enabled measurable signals up to 21 Gy per pulse, corresponding to instantaneous dose rates of 5.5 MGy/s (Milluzzo et al., 2024). Comparative measurements with an AC current transformer (ACCT) confirmed the SiC detector's ability to resolve beam current variations in real time, with integrated charge values differing by less than 7% between SiC and reference readings (Okpuwe et al., 2024). Jiménez-Ramos et al. further confirmed the long-term stability of SiC detectors irradiated with low-energy protons at mean dose rates of 10 kGy/s and DPP of 5.6 Gy, observing only a moderate sensitivity degradation of 1.34% per kGy up to 750 kGy, stabilizing within 7% after cumulative doses of several MGy (Jiménez-Ramos et al., 2025). Lopez Paz et al. demonstrated that SiC diodes can accurately measure proton UHDR beams up to 4 MGy/s with less than 3% deviation in linearity and minimal sensitivity loss after 100 kGy, supporting their use as a cost-effective alternative to diamond detectors (López Paz I. et al., 2025). Recently, Guarrera et al. presented the dosimetric characterization of a SiC detector irradiated with a 62 MeV UHDR proton beam (Guarrera et al., 2025b). The study demonstrated a linear response over a wide range of dose-rate conditions (from approximately 150 Gy/s to 230 Gy/s) and high reproducibility across multiple irradiation runs. The detector exhibited fast charge collection and negligible recombination losses, consolidating SiC as one of the most promising active dosimetric technologies for next-generation proton FLASH applications. Since earlier investigations primarily emphasized biased SiC detectors in UHDR environments, Fleta et al. extended the research by conducting a comprehensive evaluation of unbiased SiC diodes under similar conditions (Fleta et al., 2024). Their study examined several key performance indicators, including linearity, radiation hardness, time resolution, and temperature sensitivity. Linearity was assessed using a 20 MeV electron beam, with the diode exhibiting a linear response up to 10 Gy/pulse and deviations remaining within 3%. To investigate radiation-induced degradation, the linearity test was repeated following cumulative exposures exceeding 100 kGy. Under these conditions, the detector preserved linearity up to 6.5 Gy/pulse, corresponding to a sensitivity degradation rate of approximately $0.018\%/kGy$. The diode performance was further validated through percentage depth dose (PDD) measurements. Comparison with a reference PDD curve revealed a maximum deviation of only 3%, confirming the detector's suitability for beam profiling. Time-resolved measurements conducted in parallel with an integrating current transformer (ICT) demonstrated the diode's capability to accurately capture dynamic current variations during irradiation. The temperature dependence of SiC diode sensitivity was also investigated in the range of 19–38 °C. The detector response exhibited a slight linear decrease with increasing temperature, corresponding to a temperature coefficient of (−0.079 ± 0.005)%/°C. This behaviour indicates a very low thermal sensitivity compared to silicon diodes, which typically show positive temperature coefficients between 0.2% and 0.5%/°C. The observed trend confirms that SiC devices maintain stable performance over a wide temperature range, making them suitable for reliable operation in varying environmental or beam-induced thermal conditions. The low temperature dependence of SiC detectors is particularly relevant in UHDR dosimetry, where beam delivery can induce rapid local heating and temperature gradients in the detector and its surroundings. A weak thermal coefficient minimizes signal drift due to temperature fluctuations, ensuring stable charge collection and consistent sensitivity during prolonged or high-intensity irradiations. This intrinsic thermal stability enhances the reproducibility and accuracy of SiC-based dose measurements under clinical and experimental UHDR conditions.

6 Current challenges and future perspectives

Despite the significant progress achieved in the development of SiC detectors for radiotherapy dosimetry, several challenges remain that must be addressed to transition this technology from research laboratories to routine clinical implementation. One of the current practical limitations of SiC dosimetry lies in its lower signal per unit dose compared to silicon, due to the higher e–h pair creation energy (≈7.8 eV vs. 3.6 eV for Si). This is typically compensated by modern low-noise readout electronics and, in UHDR beams, can even be advantageous to mitigate saturation. Conversely, diamond, which exhibits lower sensitivity than SiC, is already widely and successfully employed for UHDR dosimetry with excellent linearity and radiation hardness, and commercial systems are available. From a cost perspective, detector-grade single-crystal diamond remains expensive and limited in wafer size, whereas SiC benefits from large-scale wafer production for power electronics; detector-grade epitaxy still requires tight control but its cost trajectory is decreasing. Therefore, in this review we consider cost a minor barrier for SiC compared to diamond at equal detector grade, while we still flag the need for consistent detector-grade epitaxy for large-area arrays (Kranzer et al., 2022; Verona et al., 2022, Verona et al., 2023; Tudisco et al., 2018; Fleta et al., 2024). While recent advances in industrial SiC wafer production driven by power electronics have improved availability, the detector-grade specifications still pose a manufacturing challenge. Another critical issue lies in the subtle non-linearities and variations in charge collection efficiency that may arise under high-dose-rate or accumulated dose conditions. Multiple studies already indicate robust radiation tolerance of SiC under UHDR electrons with cumulative doses in the 10–100 kGy range, with preserved linearity after irradiation and only small sensitivity drifts that can be tracked by routine recalibration, a procedure that remains necessary for all active dosimeters, including diamond and silicon systems. Ongoing campaigns will extend these tests to broader beam qualities and longer accumulated doses. At UHDR conditions, subtle departures from linearity and variations in charge collection efficiency (CCE) can arise due to series resistance effects and instantaneous current densities. Recent studies with SiC diodes have quantified these behaviours: biased SiC devices remain linear up to ≈5 Gy/pulse with tailored front-end electronics, and unbiased graded-junction SiC diodes have shown $< 3\%$ deviation up to ≈ 10 Gy/pulse, with a modest sensitivity degradation of ≈ 0.018 $\%kGy$ after >100 kGy accumulated dose. These results indicate that non-linearities are manageable through device/process optimization and readout design, but systematic characterizations vs. dose-per-pulse and accumulated dose remain necessary (Romano et al., 2023; Milluzzo et al., 2024; Okpuwe et al., 2024). Looking forward, several promising directions are under active investigation. The incorporation of epitaxial graphene as a transparent conductive contact has shown potential to reduce signal attenuation and minimize perturbation effects in the active region of the detector. This metal-less approach could pave the way for innovative dosimetric architectures with minimal secondary particle generation. Additionally, the design of three-dimensional SiC detector arrays or multilayer stacks may enable volumetric dose mapping with unprecedented temporal and spatial resolution, addressing the growing needs of FLASH, proton and ion therapy. Further research is also warranted to explore SiC's capabilities in extreme environments, such as *in-vivo* for real-time tumor monitoring. *In-vivo* dosimetry imposes stringent constraints that are more demanding than benchtop or phantom setups: compact form factors and cable runs prone to pickup, sterility and biocompatibility, mechanical stability on moving/respiring targets, variable temperature/humidity, possible body-fluid contact, and a dynamic dose range spanning sub-cGy (out-of-field) to clinical dose gradients within millimetres. These factors make robustness, low leakage, and stable calibration particularly critical (Bertuccio et al., 2014). Multidisciplinary collaboration among materials scientists, medical physicists, and electronics engineers will be essential to overcome current limitations and accelerate clinical translation. In summary, silicon carbide detectors represent a promising devices in radiotherapy dosimetry, offering a unique combination of radiation hardness, low noise, and real-time capability. Continued innovation in material processing, device engineering, and system integration is expected to unlock the full potential of SiC technology in the next-generation of precision radiation therapy.

Author contributions

GP: Conceptualization, Writing – review and editing, Writing – original draft. MG: Writing – review and editing. AK: Writing – review and editing, Writing – original draft, Conceptualization. ST: Writing – review and editing. CV: Writing – review and editing. GC: Investigation, Writing – review and editing, Writing – original draft.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

Adrian, G., Konradsson, E., Tinganelli, W., Loo, B. W., Pratx, G., and Durante, M. (2023). The oxygen puzzle in flash radiotherapy: a comprehensive review and experimental outlook. *Front. Oncol.* 13, 1220562. doi:10.3389/fonc.2023.1220562

Aeffner, S., Yarahmadi, M., and Sauer, O. (2013). Su - E-t-80: energy dependence of the response of a silicon diode designed for small-field dosimetry. *Med. Phys.* 40, 222. doi:10.1118/1.4814515

Altana, C., Calcagno, L., Ciampi, C., La Via, F., Lanzalone, G., Muoio, A., et al. (2023a). Radiation damage by heavy ions in silicon and silicon carbide detectors. *Sensors* 23, 6522. doi:10.3390/s2314522

Altana, C., Calcagno, L., Ciampi, C., La Via, F., Lanzalone, G., Muoio, A., et al. (2023b). Heavy-ion radiation damage in silicon and silicon carbide devices for high-radiation environments. *Sensors* 23, 6522. doi:10.3390/s23146522

Andreo, P., Burns, D. T., Kapsch, R. P., McEwen, M., and Vatnitsky, S. (2024). Absorbed dose determination in external beam radiotherapy: an international code of practice for dosimetry based on standards of absorbed dose to water. *Tech. Rep.* doi:10.21014/TRS.398Rev1

Angelou, C., Patallo, I. S., Doherty, D., Romano, F., and Schettino, G. (2024). A review of diamond dosimeters in advanced radiotherapy techniques. *Med. Phys.* 51, 9230–9249. doi:10.1002/mp.17370

Bass, G. A., Shipley, D. R., Flynn, S. F., and Thomas, R. A. S. (2022). A prototype low-cost secondary standard calorimeter for reference dosimetry with ultra-high pulse dose rates. *Br. J. Radiology* 96, 20220638. doi:10.1259/bjr.20220638

Bertuccio, G., Puglisi, D., Macera, D., Di Liberto, R., Lamborizio, M., and Mantovani, L. (2014). Silicon carbide detectors for *in vivo* dosimetry. *IEEE Trans. Nucl. Sci.* 61, 961–966. doi:10.1109/tns.2014.2307957

Borghini, A., Labate, L., Piccinini, S., Panaino, C. M. V., Andreassi, M. G., and Gizzi, L. A. (2024). Flash radiotherapy: expectations, challenges, and current knowledge. *Int. J. Mol. Sci.* 25, 2546. doi:10.3390/ijms25052546

Bourgouin, A., Hackel, T., Marinelli, M., Kranzer, R., Schüller, A., and Kapsch, R.-P. (2022). Absorbed-dose-to-water measurement using alanine in ultra-high-pulse-dose-rate electron beams. *Phys. Med. and Biol.* 67, 205011. doi:10.1088/1361-6560/ac950b

Bourhis, J., Sozzi, W. J., Jorge, P. G., Gaide, O., Bailat, C., Duclos, F., et al. (2019). Treatment of a first patient with flash-radiotherapy. *Radiotherapy Oncology* 139, 18–22. doi:10.1016/j.radonc.2019.06.019

Bruzzi, M., and Verroi, E. (2023). Epitaxial sic dosimeters and flux monitoring detectors for proton therapy beams. *Materials* 16, 3643. doi:10.3390/ma16103643

Bruzzi, M., Nava, F., Russo, S., Sciortino, S., and Vanni, P. (2001). Characterisation of silicon carbide detectors response to electron and photon irradiation. *Diam. Related Materials* 10, 657–661. doi:10.1016/s0925-9635(00)00380-0

Bruzzi, M., Bucciolini, M., Nava, F., Pini, S., and Russo, S. (2002). Advanced materials in radiation dosimetry. *Nucl. Instrum. Methods Phys. Res. Sect. A Accel. Spectrom. Detect. Assoc. Equip.* 485, 172–177. doi:10.1016/s0168-9002(02)00550-8

Capan, I. (2022). 4h-sic schottky barrier diodes as radiation detectors: a review. *Electronics* 11, 532. doi:10.3390/electronics11040532

Ciancaglioni, I., Marinelli, M., Milani, E., Prestopino, G., Verona, C., Verona-Rinati, G., et al. (2012). Dosimetric characterization of a synthetic single crystal diamond detector in clinical radiation therapy small photon beams: dosimetric characterization of a synthetic single crystal diamond detector. *Med. Phys.* 39, 4493–4501. doi:10.1118/1.4729739

Di Martino, F., Giannelli, M., Traino, A. C., and Lazzeri, M. (2005). Ion recombination correction for very high dose-per-pulse high-energy electron beams: ksat evaluation for very high dose-per-pulse electron-beams. *Med. Phys.* 32, 2204–2210. doi:10.1118/1.1940167

Di Martino, F., Del Sarto, D., Bass, G., Capaccioli, S., Celentano, M., Coves, D., et al. (2023). Architecture, flexibility and performance of a special electron linac dedicated to flash radiotherapy research: electronflash with a triode gun of the centro pisano flash radiotherapy (cpfr). *Front. Phys.* 11, 1268310. doi:10.3389/fphy.2023.1268310

Durante, M., Brauer-Krisch, E., and Hill, M. (2017). Faster and safer? Flash ultra-high dose rate in radiotherapy. *Br. J. Radiology* 20170628doi, 20170628. doi:10.1259/bjr.20170628

El Khatib, O., Simonet, C., Lemercier, M., Gondre, M., Guy, J.-B., Rancoule, C., et al. (2022). Flash irradiation induces lower levels of dna damage *ex vivo*, an effect modulated by oxygen tension, dose, and dose rate. *Radiotherapy Oncol.* 170, 44–51. doi:10.1016/j.radonc.2022.03.013

Favaudon, V., Caplier, L., Monceau, V., Pouzoulet, F., Sayarath, M., Fouillade, C., et al. (2014). Ultrahigh dose-rate flash irradiation increases the differential response between normal and tumor tissue in mice. *Sci. Transl. Med.* 6, 245ra93. doi:10.1126/scitranslmed.3008973

Ferber, R., and Hamilton, G. (1966). Silicon carbide high-temperature neutron detectors for reactor instrumentation. *Nucl. Appl.* 2, 246–251. doi:10.13182/nt66-a27595

Fleta, C., Pellegrini, G., Godignon, P., Rodríguez, F. G., Paz-Martín, J., Kranzer, R., et al. (2024). State-of-the-art silicon carbide diode dosimeters for ultra-high dose-per-pulse radiation at flash radiotherapy. *Phys. Med. and Biol.* 69, 095013. doi:10.1088/1361-6560/ad37eb

Gao, Y., Liu, Y., Zhang, Y., Li, X., Zhang, Q., Li, J., et al. (2022). A potential revolution in cancer treatment: a topical review of flash radiotherapy. *J. Appl. Clin. Med. Phys.* 23, e13790. doi:10.1002/acm2.13790

Gómez, F., Gonzalez-Castaño, D. M., Fernández, N. G., Pardo-Montero, J., Schüller, A., Gasparini, A., et al. (2022). Development of an ultra-thin parallel plate ionization chamber for dosimetry in flash radiotherapy. *Med. Phys.* 49, 4705–4714. doi:10.1002/mp.15668

Guarrera, M., Petringa, G., Tudisco, S., and Cirrone, G. (2022). Characterization of a sic detector for dosimetric application. Nuovo Cimento della Soc. Ital. Fis. C *45*. doi:10.1393/ncc/i2022-22085-8

Guarrera, M., Cirrone, G., Amato, A., Manna, C., Verona, C., Kurmanova, A., et al. (2025a). First characterization of innovative silicon carbide detectors for application in relative dosimetry with proton beams. *Nuovo Cimento della Soc. Ital. Fis. C* 48. doi:10.1393/ncc/i2025-25073-6

Guarrera, M., Petringa, G., Amato, A., Barbagiovanni, A., Catalano, R., Cuttone, G., et al. (2025b). Dosimetric characterization of a novel silicon carbide detector with uhdr proton beam. *J. Instrum.* 20, C07062. doi:10.1088/1748-0221/20/07/C07062

Guo, Q., Li, C., Zhang, L., Wang, J., Zhao, T., and Liu, X. (2024). A microscopic oxygen transport model for ultra-high dose rate radiotherapy *in vivo:* the impact of physiological conditions on the flash effect. *Med. Phys.* 51, 3462–3476. doi:10.1002/mp.17398

International Atomic Energy Agency (2013). *Development of procedures for in vivo dosimetry in radiotherapy*. In *IAEA human health report no. 8* (Vienna: International Atomic Energy Agency). doi:10.1016/0167-8140(90)90102-3

Jäger, A., Wegener, S., and Sauer, O. A. (2021). Dose rate correction for a silicon diode detector array. *J. Appl. Clin. Med. Phys.* 22, 144–151. doi:10.1002/acm2.13409

Jiménez-Ramos, M. C., Torres-Muñoz, C., García-López, J., Barroso-Molina, D., Guardiola, C., and Fleta, C. (2025). Performance of sic diodes at very high doses of low-energy proton beams under flash conditions. *IEEE Trans. Radiat. Plasma Med. Sci.* doi:10.1109/TRPMS.2025.3591229

Kakavelakis, G., Gedda, M., Panagiotopoulos, A., Kymakis, E., Anthopoulos, T. D., and Petridis, K. (2020). Metal halide perovskites for high-energy radiation detection. *Adv. Sci.* 7, 2002098. doi:10.1002/advs.202002098

Kranzer, R., Schüller, A., Bourgouin, A., Hackel, T., Poppinga, D., Lapp, M., et al. (2022). Response of diamond detectors in ultra-high dose-per-pulse electron beams for dosimetry at flash radiotherapy. *Phys. Med. and Biol.* 67, 075002. doi:10.1088/1361-6560/ac594e

Kubodera, K., Matsumoto, T., Yamaguchi, K., Yokota, R., Arai, Y., Makino, T., et al. (2023). Measurement of radiation-induced current through a sic schottky barrier diode in a clinical carbon beam cancer therapy field. *Nucl. Instrum. Methods Phys. Res. Sect. B Beam Interact. Mater. Atoms* 540, 80–84. doi:10.1016/j.nimb.2023.04.009

La Via, F., Camarda, M., and La Magna, A. (2014). Mechanisms of growth and defect properties of epitaxial sic. *Appl. Phys. Rev.* 1, 031301. doi:10.1063/1.4890974

Laub, W. U., and Crilly, R. (2014). Clinical radiation therapy measurements with a new commercial synthetic single crystal diamond detector. *J. Applied Clinical Medical Physics* 15, 92–102. doi:10.1120/jacmp.v15i6.4890

Lin, B., Gao, F., Yang, Y., Wu, D., Zhang, Y., Feng, G., et al. (2021). Flash radiotherapy: history and future. *Front. Oncology* 11, 644400. doi:10.3389/fonc.2021.644400

Lioliou, G., and Barnett, A. (2016). Gallium arsenide detectors for x-ray and electron (beta particle) spectroscopy. *Nucl. Instrum. Methods Phys. Res. Sect. A Accel. Spectrom. Detect. Assoc. Equip.* 836, 37–45. doi:10.1016/j.nima.2016.08.047

Lopez Paz, I., Fleta, C., Gomez, F., González, D. M., and Pellegrini, G. (2024). First use of silicon carbide detectors with graphene-enhanced contacts for medical dosimetry. *Sci. Rep.* 14, 6131. doi:10.1038/s41598-024-56544-x

López Paz, C., Mazza, G., Cola, A., et al. (2025). Silicon carbide diodes as active detectors for ultra-high dose rate proton beams. *Med. Phys.* doi:10.1002/mp.17976

Lopez Paz, I., Fleta, C., Ibáñez, P., Henao, Á., Sanchez-Parcerisa, D., Zazpe, A., et al. (2025). Characterization of silicon carbide diodes as cost-effective active detectors for proton UHDR dosimetry. *Med. Phys.* 52, e17986.

Mascia, A. E., Daugherty, E. C., Zhang, Y., Lee, E., Xiao, Z., Sertorio, M., et al. (2023). Proton flash radiotherapy for the treatment of symptomatic bone metastases: the fast-01 nonrandomized trial. *JAMA Oncology* 9, 62–69. doi:10.1001/jamaoncol.2022.5843

Matsumoto, T., Yamaguchi, K., Yanagisawa, R., Kubodera, K., Arai, Y., Makino, T., et al. (2023). Development of a sic semiconductor-based dosimeter for evaluating clinical dose distribution in carbon ion cancer therapy fields. *Nucl. Instrum. Methods Phys. Res. Sect. B Beam Interact. Mater. Atoms* 542, 151–157. doi:10.1016/j.nimb.2023.06.013

Matsunami, H., and Kimoto, T. (1997). Step-controlled epitaxial growth of sic: high quality homoepitaxy. *Mater. Sci. Eng. R Rep.* 20, 125–166. doi:10.1016/s0927-796x(97)00005-3

Medina, E., Ferro, A., Abujami, M., Camperi, A., Centis Vignali, M., Data, E., et al. (2024). First experimental validation of silicon-based sensors for monitoring ultra-high dose rate electron beams. *Front. Phys.* 12, 1258832. doi:10.3389/fphy.2024.1258832

Milluzzo, G., De Napoli, M., Di Martino, F., Amato, A., Del Sarto, D., D'Oca, M. C., et al. (2024). Comprehensive dosimetric characterization of novel silicon carbide detectors with uhdr electron beams for flash radiotherapy. *Med. Phys.* 51, 6390–6401. doi:10.1002/mp.17172

Montay-Gruel, P., Petit, B., Benderitter, M., Petersson, K., and Favaudon, V. (2023). Proton flash effects on mouse skin at different oxygen tensions. *Radiat. Environ. Biophysics* 62, 297–310. doi:10.1007/s00411-023-00984-8

Náfrádi, B., Náfrádi, G., Forró, L., and Horváth, E. (2015). Methylammonium lead iodide for efficient x-ray energy conversion. *J. Phys. Chem. C* 119, 25204–25208. doi:10.1021/acs.jpcc.5b07876

Nava, F., Bertuccio, G., Cavallini, A., and Vittone, E. (2008). Silicon carbide and its use as a radiation detector material. *Meas. Sci. Technol.* 19, 102001. doi:10.1088/0957-0233/19/10/102001

Okpuwe, C., Amato, A., D'Amico, I., De Liso, V., De Napoli, M., Di Martino, F., et al. (2024). Silicon carbide detectors for dosimetry and monitoring of ultra-high dose rate beams. *J. Instrum.* 19, C03064. doi:10.1088/1748-0221/19/03/c03064

Palmans, H., Thomas, R., Simon, M., Duane, S., Kacperek, A., DuSautoy, A., et al. (2004). A small-body portable graphite calorimeter for dosimetry in low-energy clinical proton beams. *Phys. Med. Biol.* 49, 3737–3749. doi:10.1088/0031-9155/49/16/019

Pearton, S., Ren, F., Patrick, E., Law, M., and Polyakov, A. Y. (2015). Review—ionizing radiation damage effects on GaN devices. *ECS J. Solid State Science Technology* 5, Q35–Q60. doi:10.1149/2.0251602jss

Petringa, G., Cirrone, G., Altana, C., Puglia, S., and Tudisco, S. (2020). First characterization of a new silicon carbide detector for dosimetric applications. *J. Instrum.* 15, C05023. doi:10.1088/1748-0221/15/05/c05023

Petringa, G., Cirrone, G., Guarrera, M., Kurmanova, A., Amato, A., Catalano, R., et al. (2022). Prague (proton range measurement using silicon carbide): a detector to measure online the proton beam range with laser-driven proton beams.

Petringa, G., Catalano, R., Amato, A., Russo, A. D., Fustaino, G. F., Guarrera, M., et al. (2025a). Design and validation of an integrated reference dosimetry and monitoring system for ultra-high dose-rate proton beams ranging from 20 gy/s to 230 gy/s. *Phys. Medica* 138, 105187. doi:10.1016/j.ejmp.2025.105187

Petringa, G., Verona, C., Catalano, R., Guarrera, M., Kurmanova, A., Brighel, L., et al. (2025b). "Toward the use of silicon-carbide–based detector for protontherapy microdosimetry," in *Proceedings of the 111th Italian physical society national congress (SIF 2025)* (Palermo, Italy: Società Italiana di Fisica).

Pittet, P., Jalade, P., Balosso, J., Gindraux, L., Guiral, P., Wang, R., et al. (2015). Dosimetry systems based on gallium nitride probe for radiotherapy, brachytherapy and interventional radiology. *IRBM* 36, 92–100. doi:10.1016/j.irbm.2015.01.008

Posar, J. A., Davis, J., Large, M. J., Basiricò, L., Ciavatti, A., Fraboni, B., et al. (2020). Characterization of an organic semiconductor diode for dosimetry in radiotherapy. *Med. Phys.* 47, 3658–3668. doi:10.1002/mp.14229

Rafi, J. M., Pellegrini, G., Godignon, P., Ugobono, S. O., Rius, G., Tsunoda, I., et al. (2020). Electron, neutron, and proton irradiation effects on sic epitaxial diodes for radiation detection. *IEEE Trans. Nucl. Sci.* 67, 2658–2665. doi:10.1109/TNS.2020.3029730

Romano, F., Bailat, C., Jorge, P. G., Lerch, M. L. F., and Darafsheh, A. (2022). Ultra-high dose rate dosimetry: challenges and opportunities for flash radiation therapy. *Med. Phys.* 49, 4912–4932. doi:10.1002/mp.15649

Romano, F., Milluzzo, G., Di Martino, F., D'Oca, M. C., Felici, G., Galante, F., et al. (2023). First characterization of novel silicon carbide detectors with ultra-high dose rate electron beams for flash radiotherapy. *Appl. Sci.* 13, 2986. doi:10.3390/app13052986

Sellin, P., and Vaitkus, J. (2006). New materials for radiation hard semiconductor dectectors. *Nucl. Instrum. Methods Phys. Res. Sect. A Accel. Spectrom. Detect. Assoc. Equip.* 557, 479–489. doi:10.1016/j.nima.2005.10.128

Stavro, J., Goldan, A. H., and Zhao, W. (2018). Photon counting performance of amorphous selenium and its dependence on detector structure. *J. Med. Imaging* 5, 1. doi:10.1117/1.jmi.5.4.043502

Tudisco, S., La Via, F., Agodi, C., Altana, C., Borghi, G., Boscardin, M., et al. (2018). Sicilia—Silicon carbide detectors for intense luminosity investigations and applications. *Sensors* 18, 2289. doi:10.3390/s18072289

Verona, C., Parisi, G., Cesaroni, S., Crnjac, A., Jakšić, M., Marinelli, M., et al. (2022). Characterisation of a monolithic ΔE-E diamond telescope detector using low energy ion microbeams. *Radiat. Meas.* 159, 106875. doi:10.1016/j.radmeas.2022.106875

Verona, C., Barna, S., Georg, D., Hamad, Y., Magrin, G., Marinelli, M., et al. (2023). Diamond based integrated detection system for dosimetric and microdosimetric characterization of radiotherapy ion beams. *Med. Phys.* 51, 533–544. doi:10.1002/mp.16698

Vignati, A., Giordanengo, S., Fausti, F., Martì Villarreal, O. A., Mas Milian, F., Mazza, G., et al. (2020). Beam monitors for tomorrow: the challenges of electron and photon flash rt. *Front. Phys.* 8, 375. doi:10.3389/fphy.2020.00375

Vozenin, M.-C., Bourhis, J., and Durante, M. (2022). Towards clinical translation of flash radiotherapy. *Nat. Rev. Clin. Oncol.* 19, 791–803. doi:10.1038/s41571-022-00697-z

Wolf, L., Kuess, P., Leitner, S., Georg, D., and Knäusl, B. (2025). Commissioning of a precision preclinical 200 kv x-ray irradiator based on modular adaptations. *Med. Phys.* 52, 4713–4722. doi:10.1002/mp.17758

Yadav, M., Pradhan, K., and Sahu, P. (2016). A complete analytical potential based solution for a 4h-sic mosfet in nanoscale. *Adv. Nat. Sci. Nanosci. Nanotechnol.* 7, 025011. doi:10.1088/2043-6262/7/2/025011

Zhang, F. (2015). "High-responsivity sic ultraviolet photodetectors with sio2 and al2o3 films," in *Advanced silicon carbide devices and processing*, 199–220.