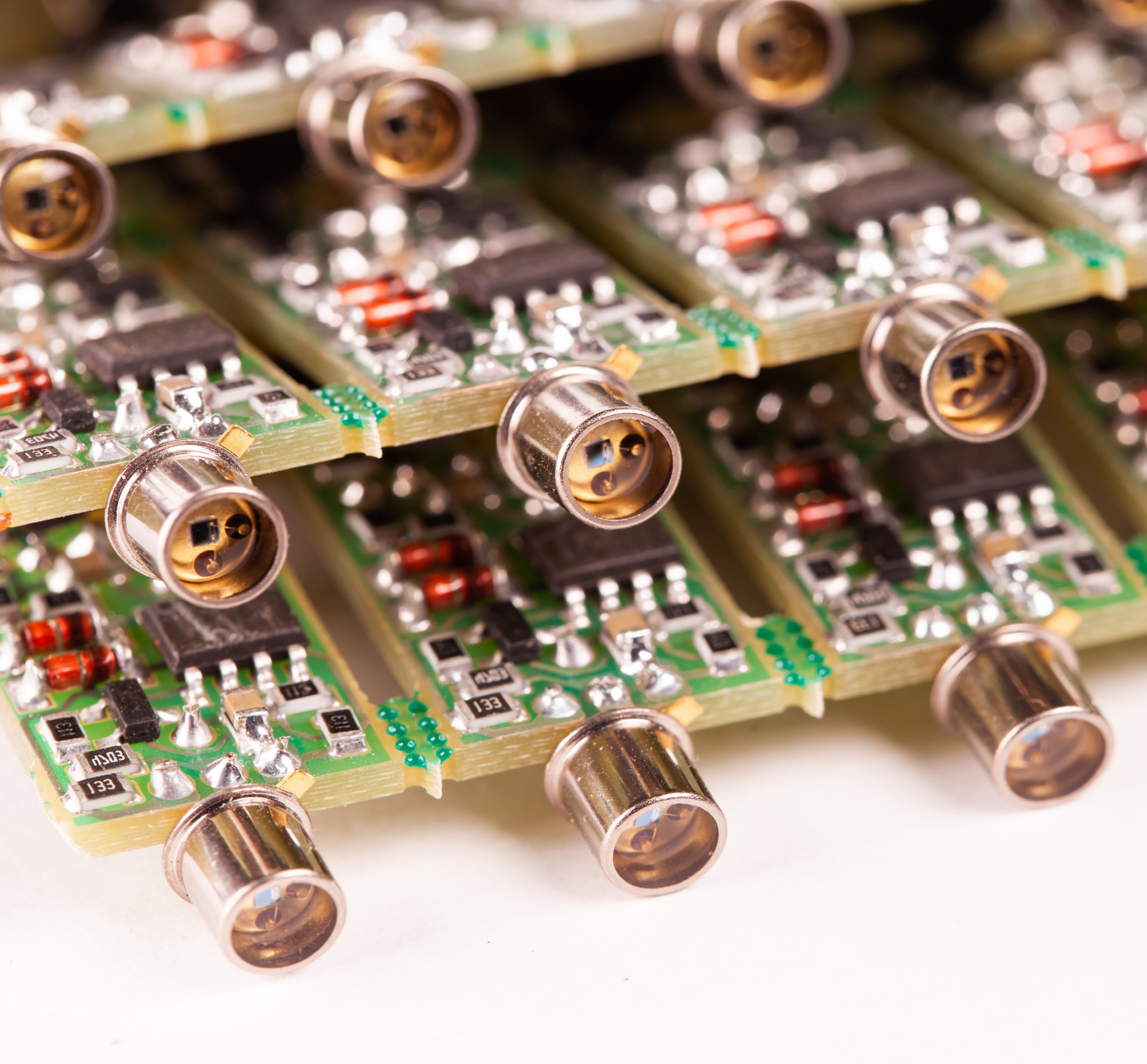

CoolCAD ELECTRONICS

SiC for the rest of us

Linear and Avalanche Diodes for Harsh and High-Temperature Environments

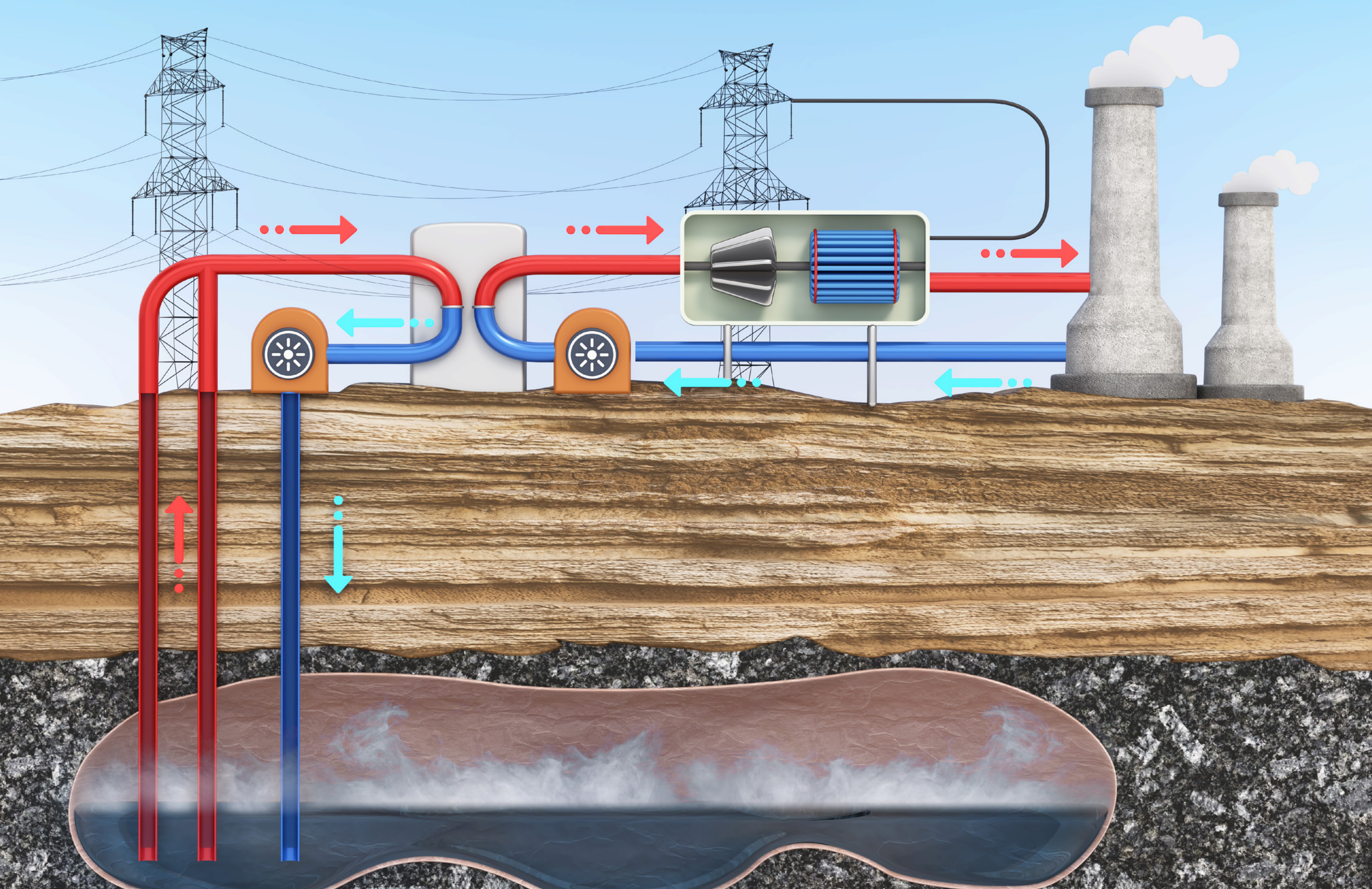

Illustration of geothermal energy production

Photon detection technologies form the backbone of a wide array of modern instrumentation systems, spanning oil and gas exploration, geothermal energy harvesting, industrial flame detection, aerospace sensing, and environmental spectroscopy. These diverse applications share a common demand: detectors capable of resolving sometimes extremely low-light or single-photon signals while surviving the potentially punishing mechanical and thermal conditions of their operating environments. Conventional silicon-based photodiodes and photomultiplier tubes (PMTs) have long fulfilled this role, but both technologies exhibit critical shortcomings when pushed into the high-temperature, high-vibration, or high-radiation regimes that characterize today's industrial and scientific frontier.

CoolCAD Electronics is advancing a new generation of silicon carbide (SiC) linear and avalanche photodiodes (APDs) engineered for exceptional performance in extreme conditions. By leveraging SiC's wide bandgap, high breakdown electric field, and excellent thermal tolerance, these devices combine high gain with low noise even at temperatures exceeding 300°C. They are intended to replace the fragile, high-voltage PMTs and the high-temperature-intolerant silicon detectors currently used in harsh-environment sensing applications.

The origins of this technology development lie in the downhole instrumentation systems used for natural gas, oil, and geothermal drilling. During drilling, geophysical sensors identify subsurface formations by detecting gamma-ray emissions that correlate with specific rock types such as shale. Because gamma rays are nearly impossible to detect directly, the industry uses scintillator crystals that convert high-energy gamma photons into lower-energy visible or ultraviolet photons. The resulting optical signal is weak, often only a few photons per event, and thus requires detectors with intrinsic amplification and extremely low noise levels.

Historically, this role has been served by photomultiplier tubes, vacuum-based devices capable of generating gains of 10^6 or higher. Despite their sensitivity, PMTs are mechanically fragile, relatively large, and extremely expensive. They require bias voltages approaching a kilovolt, which are difficult to deliver and regulate hundreds of meters below ground. Moreover, the combination of vibration, thermal cycling, and pressure inherent to deep-well operations frequently leads to PMT breakage and replacement.

CoolCAD's silicon carbide APDs address each of these challenges simultaneously. The devices achieve strong avalanche gain at bias voltages of only 180 – 200 V, with future designs expected to function near 100 V, an order of magnitude lower than PMT operating voltages. This greatly simplifies the power-supply architecture, improving system reliability. Because they are monolithic solid-state devices, SiC APDs offer high mechanical durability and compact form factors suitable for printed-circuit-board integration.

At the core of their performance lies the physics of the avalanche process. In a linear photodiode, each absorbed photon generates one electron–hole pair (EHP) in the semiconductor depletion region. The electric field sweeps these carriers to the contacts, producing a photocurrent directly proportional to incident light intensity. Although linear operation provides excellent linearity and dynamic range, it cannot detect single-photon events, since the charge generated by one photon, on the order of 10^{-19} A, is far below detection limits without external amplification.

In contrast, avalanche photodiodes operate near their breakdown voltage. When a photon creates an electron–hole pair, the carriers are accelerated by the high field and collide with the lattice, liberating additional pairs through impact ionization. This cascading effect results in internal current multiplication; one photon can trigger a million carriers. Avalanche gain of approximately 10^6 enables single-photon sensitivity without external amplification circuits.

Traditional silicon APDs, however, suffer from catastrophic performance degradation at elevated temperatures. Thermal excitation drastically increases dark current and noise, overwhelming the photon-generated signal. At around 150°C, the noise in silicon devices can render them ineffective, especially for low light levels. SiC's wide bandgap (~3.2 eV) reduces the intrinsic carrier concentration by many orders of magnitude, keeping the dark current extremely low even at 250 – 300°C. Its critical electric field strength (2 – 3 MV/cm) permits high avalanche fields without premature breakdown. The combination of these properties results in a detector that maintains both low noise and high gain under extreme thermal stress, enabling applications far beyond the reach of silicon devices.

Noise suppression is one of the defining attributes of SiC photodiodes. The intrinsic noise level is often so low that, as noted in CoolCAD's internal testing, it falls beneath the noise floor of the measurement system itself. This characteristic translates into an inherently higher signal-to-noise ratio and allows precise discrimination between true photon events and dark counts. The dark count rate, representing spurious current pulses not triggered by photons, remains exceptionally low even at high temperature, enabling stable single-photon detection without excessive signal processing.

Mechanical and packaging design play an equally vital role in enabling field deployment. Downhole assemblies experience continuous vibration, mechanical shock, and steep thermal gradients. PMTs, with their glass housings, are prone to fracture and are difficult to mount securely. In contrast, SiC photodiodes are small, solid-state, and easily integrated into standard electronics. These dies can be attached directly to printed circuit boards as bare-die wire-bonded chips, protected with dam-and-fill encapsulants, or molded into packages with UV-transparent lids, using quartz, sapphire, or specialized high-temperature polymers. CoolCAD is also exploring molding compounds rated up to 250°C, originally developed for SiC power transistor packaging. At these limits, a combination of encapsulation and external heat shielding may be required, but the solid-state design still vastly outperforms vacuum-tube reliability.

Optical packaging enhancements such as ball-lens coupling or multi-die arrays can increase the effective light-collection area. This approach circumvents one of the key constraints of avalanche diodes, premature breakdown caused by local crystalline defects, by distributing the optical input across several smaller, well-behaved devices. The company's development roadmap includes work toward such scalable arrays for higher sensitivity and larger field-of-view instruments.

At the system level, a functioning detector assembly extends well beyond the photodiode itself. Each device requires a stable reverse-bias source, typically 100 – 200 V, a readout network consisting of series resistors to limit avalanche current and shunt resistors to develop measurable voltage, and amplifier circuitry for pulse shaping and discrimination. In downhole or geothermal probes, these components must operate close to the sensor to minimize noise pickup and signal loss. The processed signal is then transmitted through high-temperature copper wiring hundreds of meters to surface controllers.

Because transmitting faint analog signals over long cables is impractical, the systems incorporate local logic and amplification electronics within the downhole module. These circuits, often built in silicon-on-insulator (SOI) technology, can tolerate temperatures up to approximately 225°C. They convert the APD's discrete current pulses into clean digital signals or integrated pulse counts before sending data to the surface. The result is a compact, ruggedized sensor assembly combining photon detection, analog amplification, and digital communication in a thermally challenging environment.

The benefits of silicon carbide photodiodes extend beyond subterranean sensing. Their UV-only spectral response and thermal resilience open the door to numerous complementary applications. One prominent example is flame detection in industrial furnaces, gas turbines, and safety systems. Flames emit UV radiation during ignition, well before visible light or smoke appears. Silicon detectors respond to a broad spectrum and require optical filters to isolate UV wavelengths, which adds cost and complexity. SiC photodiodes, naturally insensitive to visible and infrared light, detect UV emissions directly and reject background illumination without filtering, offering more reliable and faster flame detection under bright conditions.

A related application lies in rocket plume monitoring, atmospheric trace gas detection, and other aerospace diagnostics, where UV emissions must be detected against intense visible backgrounds. SiC's radiation hardness and thermal tolerance make it well suited for operation near propulsion systems and in spaceborne instruments.

CoolCAD is also developing linear SiC photodiodes for spectroscopic sensing in collaboration with NASA. These devices operate without avalanche gain but provide stable, low-noise UV detection for environmental monitoring and planetary exploration. Arrays of such photodiodes can detect absorption spectra of key gases, including formaldehyde and water vapor, supporting missions aimed at mapping chemical compositions of planetary atmospheres or the Lunar surface. The eventual adaptation of avalanche gain to array architectures could revolutionize UV spectroscopy, enabling compact, single-photon-sensitive imagers for deep-space science.

Ongoing research at CoolCAD focuses on refining device performance through materials, process, and integration improvements. Reducing defect densities in epitaxial SiC layers minimizes localized field enhancements that lead to premature breakdown and noise. Advances in ion implantation and doping control allow precise shaping of electric-field profiles to achieve uniform avalanche multiplication. Engineers are also exploring heterostructure designs and doping gradients to optimize impact-ionization coefficients for both electrons and holes, improving gain stability across wide temperature ranges.

The company's long-term roadmap includes monolithic integration of SiC APDs and linear photodiodes with on-chip readout and logic electronics. Such integration would produce compact, hermetically sealed detection modules capable of autonomous operation at 300°C, ideal for geothermal, aerospace, and nuclear monitoring systems. Additionally, the extension of avalanche technology into multi-element arrays could provide transformative capabilities in imaging, lidar, and spectroscopic sensing, combining the ruggedness of wide-bandgap semiconductors with the sensitivity traditionally limited to cryogenic photon-counting devices.

When compared side by side with conventional detector technologies, the performance advantages are striking. Silicon carbide photodiodes offer PMT-class gain within a semiconductor package, operate at 10% of the voltage, and maintain functionality at three times the temperature. They deliver dark-current suppression exceeding ten orders of magnitude over silicon at equivalent thermal conditions. Unlike PMTs, they are hardier to mechanical shock and vibration, occupy minimal board space, and integrate seamlessly with modern electronics.

This convergence of attributes positions SiC photodiodes as the enabling technology for the next generation of extreme-environment UV optical sensing. They provide the foundation for robust, low-power, and maintenance-free instruments that can function in the world's hottest, deepest, and most radiation-intense settings.

In summary, silicon carbide's inherent material properties, wide bandgap, high breakdown field, low leakage current, and superior high temperature performance, make it the ideal semiconductor for advancing both linear and avalanche photodiode architectures. CoolCAD Electronics' work demonstrates how these properties translate from physics into application-ready devices capable of replacing legacy PMTs and extending optical sensing to entirely new frontiers. As the technology matures toward integrated arrays and on-chip electronics, it promises to redefine performance expectations for photodetection in the most demanding conditions found on Earth and beyond.

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About CoolCAD

CoolCAD Electronics is a leader in the development and fabrication of SiC-based power devices and high-temperature semiconductor electronics for aerospace, automotive, defense, geothermal development, green energy production, industrial furnace control, water purification, and oil and gas extraction. The CoolCAD team possesses a unique combination of expertise in electronics, semiconductor physics, fabrication, and design. They also excel at integrated and board-level circuit development and manufacturing. They have published 100s of research papers in professional scientific and engineering journals, and have multiple patents on their key discoveries in the area of wide bandgap SiC electronics.

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