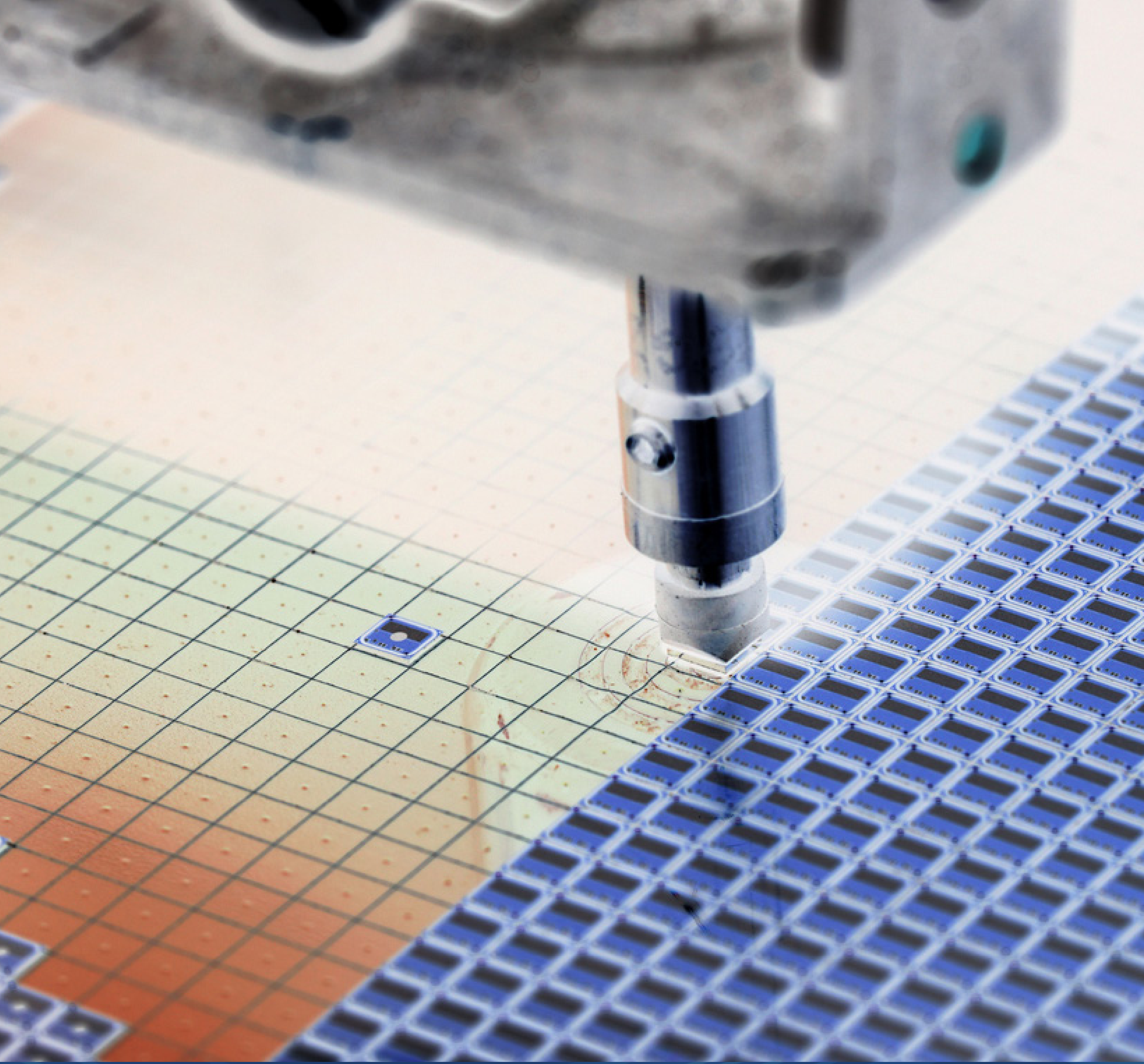


The Future of Metal-Oxide-Semiconductor (MOS) Based Technology

CoolCAD ELECTRONICS

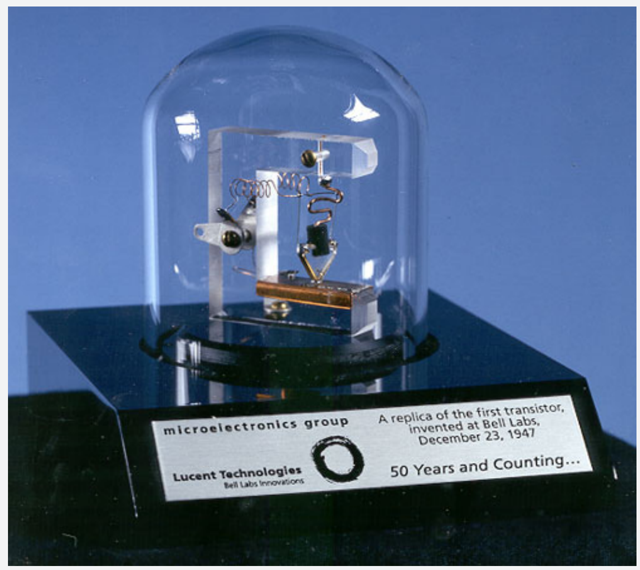
SiC for the rest of us

CoolCAD Electronics Enables New Applications and Opportunities with Silicon Carbide (SiC) Solutions

Abstract

Metal Oxide Semiconductor (MOS) technology plays a crucial role in modern electronics. This paper explores the reasons why this technology is so pervasive by briefly looking at its history and current trends. The discussion then shifts to recent innovations that are influencing both present and future applications, highlighting recent developments made by CoolCAD Electronics, a semiconductor technology firm that is revolutionizing transistor manufacturing through their exclusive design and fabrication processes for silicon carbide (SiC) MOS integrated circuits. The discussion concludes by examining emerging smart technology applications for SiC-based CMOS integrated circuits (ICs) capable of operating in harsh high-temperature environments.

History



Since their invention at Bell Labs in 1959, Metal Oxide Semiconductor Field-Effect Transistors (MOSFETs) have become the backbone of modern electronics. Their versatility is unparalleled due to their ability to function as amplifiers, switches, voltage regulators, current regulators, and microprocessors, making them fundamental components in a wide range of electronic devices. From smartphones, computers and LED lighting to automotive electronics, power generation and space exploration, applications for MOSFETs are numerous.

MOS based technology rapidly evolved in the 1960s with the development of NMOS (n-type) and PMOS (p-type) MOSFETs, each exhibiting distinct characteristics, due to differing fabrication methods and semiconductor doping strategies. NMOS transistors were faster than PMOS transistors. Whereas PMOS transistors consumed less power and were less prone to noise than NMOS transistors. Selecting the right type of MOSFET for a specific application typically involved weighing the advantages and disadvantages of each type.

The CMOS transistor was invented in the mid-1960s by Frank Wanlass at Fairchild Semiconductor. Wanlass wanted to address the inherent trade-offs between n-type and p-type transistors by incorporating both types into a single integrated circuit (IC). When used together in symmetrical (complementary) NMOS-PMOS pairs, they provide a balance between speed and power efficiency, while generating less heat. Because power consumption and heat generation are major concerns in IC design, CMOS technology found wide application in microprocessors, microcontrollers, memory chips and other digital logic circuits, and also became favored in analog circuits for image sensors, data converters, RF circuits and highly integrated transceivers.

MOS based technology has continued to evolve and progress, marked by a multitude of patented design variations and enhancements in both performance and fabrication efficiencies. These developments have firmly established MOS based transistors as integral elements within the electronics industry, demonstrated by their widespread prevalence.

Pushing the Limits of Conventional Silicon-Based MOS Technology

Silicon (Si) was quickly adopted as the base material for MOS transistors and continues to be the mainstream choice for many applications today. Although silicon has served transistors well for decades, multiple trends are pushing the limits of conventional silicon-based designs.

Harsh operating conditions and stringent reliability standards in the aerospace, transportation, military, and energy sectors of the electronics industry have placed significant demands on the capabilities of conventional silicon-based MOS technology. These sectors are actively championing research and development programs in search of higher performance alternatives to silicon. Agencies such as NASA, DARPA, and others are collaborating with technology firms, academia, and laboratories to foster advancements that support their needs for higher performance and reliability in harsh high-temperature environments.

Consumer demands for compact, lightweight, and smarter devices are pushing miniaturization and higher power densities. Although innovations such as high-density interconnect (HDI) PCBs and 2.5D and 3D semiconductor packaging are propelling the industry forward in these areas, challenges must still be addressed. Perhaps the most urgent concern is thermal reliability, driving the need for advanced semiconductor fabrication materials and methods that produce devices capable of withstanding elevated temperatures that result from increased power and functionality in confined spaces.

Emerging technologies like artificial intelligence (AI) will likely play increasingly dominant roles in the future of MOS based technology. From self-driving cars to facial recognition, these computationally intensive systems are being harnessed in many practical applications, demonstrating tangible benefits, and generating widespread curiosity about potential future applications. Very Large-Scale Integration (VLSI) with billions of CMOS transistors are needed to power large numbers of simultaneous high-frequency mathematical calculations and logic operations for AI. Researchers agree that the realization of AI's full potential, particularly in the context of autonomous AI systems operating in harsh high-temperature environments, hinges on continued advancements in CMOS materials and fabrication technologies.

These trends, and others, are collectively pushing the industry beyond the capabilities of traditional silicon, influencing the future trajectory of MOS based technology.

Wide Bandgap Silicon Carbide (SiC) – A Robust Alternative to Conventional Silicon (Si)

In recent years, wide bandgap semiconductor materials such as silicon carbide (SiC) and gallium nitride (GaN) have become the focus of much research in the pursuit of alternatives to silicon for the most demanding applications.

In my role at CoolCAD Electronics, I am proud to be actively engaged in initiatives focused on developing advanced SiC-based semiconductor alternatives to traditional silicon technology. CoolCAD is one of a few elite technology companies that have been awarded multiple Phase I and Phase II research grants from organizations such as NASA, DARPA, ARL and OSD. These grants, along with private and corporate investments, support the development of our design and manufacturing programs for SiC-based MOS electronics.

In my work, I have witnessed firsthand the superior physical and electrical properties that can be achieved with wide bandgap SiC-based semiconductors compared to those based on conventional silicon. For example, SiC-based semiconductors possess:

- Superior high-temperature tolerance with 3X higher thermal conductivity.
- Notably lower coefficients of thermal expansion, safeguarding fragile interconnections from stress cracking, which may occur due to temperature-induced expansions and contractions.
- Improved durability, with hardness second only to diamond, and high resistance to abrasion, corrosion, and radiation.
- 10X higher critical electric field strength than those based on silicon, for superior blocking voltage and faster power switching.

Furthermore, like silicon, SiC possesses the ability to grow a native oxide layer. This feature distinguishes it from every other wide bandgap semiconductor. The native oxide layer serves as a crucial dielectric insulator between MOSFET drain and source, playing a key role in controlling threshold voltage (Vt) and gate-source voltages (VGS).

CoolCAD's Unique Approach to Designing Advanced SiC MOS Based Integrated Circuits

Designing and fabricating SiC semiconductors involves numerous complexities and challenges. SiC exists in various crystal structures, known as polytypes, and only a limited number can be reproduced in a form that is suitable for semiconductor applications. In addition, material properties are influenced by numerous variables, from the arrangement of atoms within the SiC crystal lattice to different doping materials and strategies.

At CoolCAD, computer modeling is fundamental in our approach to designing and fabricating SiC-based MOS semiconductors. In particular, we use Density Functional Theory (DFT), a statistical simulation technique for predicting electrical, thermal, mechanical, optical, and other properties for distinct SiC crystal and amorphous structures at the atomic scale. DFT is an important tool that guides our design and fabrication procedures, contributing to the exceptional high-temperature resilience we have achieved in our SiC-based MOS devices.
Our devices are engineered to function at temperatures that surpass, by hundreds of degrees, the 200°C thermal capability of conventional silicon-based chips. For example,

- CoolCAD has developed technology for designing and fabricating MOSFETs based on silicon carbide (SiC) capable of functioning at temperatures reaching as high as 600°C. Their exceptional high temperature resilience is attributed to our unique gate structure, a result of our proprietary fabrication method for gate oxide growth and the unique geometric structure implemented during patterning the gate.
- CoolCAD has established an exclusive process for manufacturing SiC CMOS integrated circuits capable of functioning at temperatures up to 500°C, using formulations crafted and implemented by our own engineers. While other companies limit their focus to SiC-based power transistors, CoolCAD is the only company that has an active development program for SiC-based CMOS ICs.
- Perhaps even more significant, CoolCAD has demonstrated NMOS amplifier circuits that have operated continuously at 400°C for significantly more than 100 uninterrupted hours, without degradation.

Expanding the Boundaries of Smart Technology with SiC-Based CMOS Integrated Circuits (ICs)

CMOS ICs play a pivotal role in smart technology for harsh environments. Their distinct architecture makes them ideal for Very Large-Scale Integration (VLSI), allowing billions of transistors to be integrated into a single chip. Together, CMOS and VLSI enable intelligence within smart devices by powering numerous, simultaneous, high-frequency mathematical calculations and logic operations, along with wireless communications with other smart devices, computers, and controllers.

At CoolCAD, we have developed a proprietary fabrication process for SiC-based CMOS ICs. Figure 1 shows a wafer of SiC devices and integrated circuits. The SiC CMOS logic gates were rigorously tested and confirmed high-temperature stable at 500°C. These test results demonstrate the high-temperature potential of our SiC-based CMOS technology.

Currently, monitoring and control in high-temperature environments is cumbersome. It typically involves using a specialized sensor (designed for stability in elevated temperatures) that takes readings and transmits data through long wires to a computer and control module located in a secure room temperature setting. This configuration undermines the efficacy of the process. The extended separation between sensor and control module exposes readings to interference, diminishes sensitivity, and lengthens the time it takes to actuate control. Furthermore, this setup is unwieldy due to the added weight of lengthy wires and the potential for wire damage.

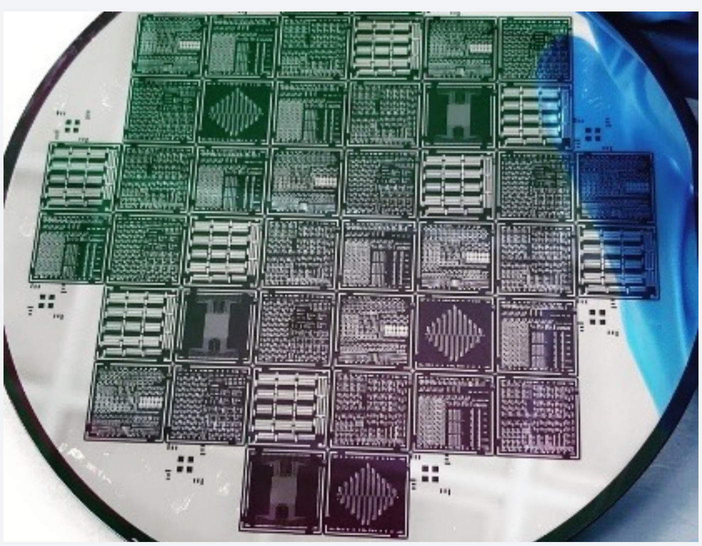


Figure 1 – Wafer of SiC Devices & ICs

By contrast, in room temperature settings, smart monitoring and control is employed with a single smart sensor, integrated to internally digitize, store, and process data on a single chip. Information can be transmitted and received wirelessly, seamlessly communicating with other smart chips that can actuate autonomous control.

At CoolCAD, we are at the forefront of advancing high-temperature monitoring and control systems using SiC-based CMOS IC technology for in-situ sensing, data storage and processing capabilities. Our expertise lies in designing and fabricating CMOS ICs that are stable at high temperatures and tailored to meet your specific needs. Whether it’s for smart power generation, monitoring and control of aircraft, rocket, and automotive engines, or applications in oil, gas and geothermal drilling and furnace exhaust systems, our technology is versatile across a wide range of applications. The benefits extend widely, encompassing optimized energy generation efficiencies, detection of defects, prediction of hazardous events, the extension of the operational life of critical equipment and much more.

Conclusion

The journey from the historic foundations of early NMOS and PMOS transistors to cutting-edge CMOS-VLSI smart technology showcases an industry with unwavering commitment to innovation. CoolCAD proudly continues to lead this charge, with our SiC-based transistors already delivering substantial high-performance improvements in the aerospace, automotive, defense, energy, and industrial sectors.

Our next objective is to push the boundaries of smart CMOS integrated circuits, enabling in-situ data logging and processing in the most challenging high-temperature environments. Given current trends and developments, SiC-based CMOS technology will have a lasting presence, enabling new opportunities with applications and benefits that are virtually limitless.

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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.

To learn more about CoolCAD visit **coolcadelectronics.com**