ISSN (Online): 2583-648X

IJIRID

International Journal of Ingenious Research, Invention and Development

An International, High Impact Factor, Double-Blind Peer-Reviewed, Open-Access, Multidisciplinary Online Journal

Volume 5 | Issue 2 | April 2026

www.ijirid.in

Advance Nanoelectronics VLSI System

Prof. S. R. Chaudhri, Vaibhavi P. Deshmukh, Anandi S. Pete

Department of Electronics & Telecomm. Eng, DRGIT&R, Amravati, India

Abstract: *This abstract explores the design challenges and innovations associated with nano-electronic VLSI, including short-channel effects, leakage power, variability, reliability, and thermal management. An advanced nanoelectronics VLSI system generally discusses the integration of nanoscale devices and materials into highly complex, very-large-scale integration (VLSI) circuits to overcome the limitations of traditional CMOS scaling. Advancement in nanoelectronics and VLSI technology have enabled the development of compact, high-speed, and low-power embedded system. That are smaller in size, faster in operation, and consume less power. This project Presents and Advanced Nan-electronic VLSI system design designed using a PIC16F873A microcontroller for intelligent control and monitoring application. The PIC16F873A microcontroller is used as the main control unit, MAX232 enables serial communication, ULN 2803 functions as a relay driver, and HCPI-800J provides electrical isolation and signal conditioning. The Proposed system highlights effective integration of hardware and software , makings its well suited for automation and control application . The role of advanced fabrication processes , including extreme ultra-violet (EUV) lithography and 3D integration is for enabling next – generation VLSI systems.*

I. INTRODUCTION

Advanced nano-electronic VLSI systems refer to integrated circuits designed and fabricated using nano-meter-scale technologies, typically below 100 nm, where device dimensions approach atomic scales. As scaling approaches fundamental physical limits, future nano- electronic VLSI research focuses on 3D integration, quantum devices, neuromorphic computing, and beyond-CMOS technologies, shaping the next generation of intelligent electronic systems. Nano-electronics further improves system performance by operating at nano-meter-scale dimensions. Embedded systems developed using VLSI principles are extensively used in industrial automation, communication systems, and real-time monitoring applications.

This project focuses on the design of a nano-electronic embedded system using standard VLSI components and interfacing methods. These systems play a critical role in applications such as high-performance computing, mobile and embedded systems, Internet of Things (IoT), biomedical devices, and artificial intelligence accelerators.

As scaling approaches fundamental physical limits, future nano-electronic VLSI research focuses on 3D integration, quantum devices, neuromorphic computing, and beyond-CMOS technologies,shaping the next generation of intelligent electronic systems.

- Memory write location: the memory address at which data is written and saved.
- Memory write logic: the control circuitry that directs and performs the process of storing data in memory.

DOI 10.5281/zenodo.19500630

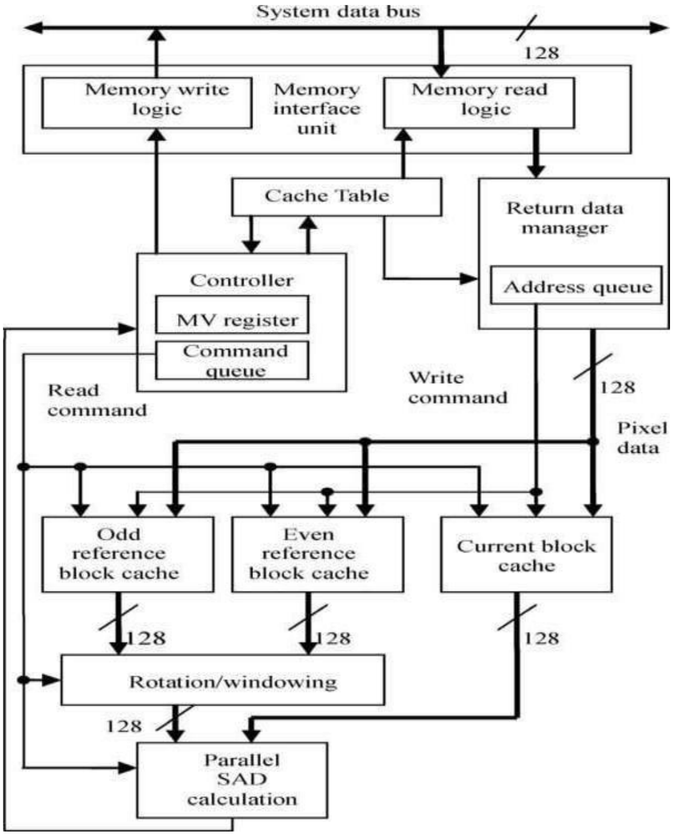

Figure 1: FUNCTION REQUIREMENTS

- Memory read logic describes the operations, control signals, and hardware elements such as decoders and sense amplifiers—used to access and retrieve stored binary data from a designated address in a memory device (RAM or ROM)
- The MIU is the hardware bridge that connects the processor to the memory system. It manages data transfers, generates necessary addresses, and sends control signals to ensure read/write operations happen correctly".
- A cache table is a database structure that keeps commonly used, infrequently updated data in fast local memory (RAM) so it can be accessed quickly without repeatedly fetching it from a slower external source.
- A controller serves as the middleman in the Model-View-Controller (MVC) framework. Its main role is to handle incoming requests—usually from a user's browser—figure out the required actions, pass tasks to the relevant models or business logic, and then decide what response (view or data) should be returned to the user.
- A resistor is a passive electronic device with two terminals that provides a set amount of resistance in a circuit. Its main purposes are to control or reduce the flow of electric current, split voltages, and release surplus electrical energy as heat.
- A command queue is a computing data structure that stores a series of tasks or instructions waiting to be carried out by a device, like a CPU, GPU, or storage drive.

DOI 10.5281/zenodo.19500630

- A Return Date Manager is a system or tool that keeps track of when borrowed items—like library books, rental equipment, or other assets—are due. It helps ensure items are returned on time, sends reminders if needed, and helps both users and administrators stay organized.
- An address queue is a messaging endpoint where messages are delivered to a uniquely identified address and then distributed to one or more linked queues according to the routing method set (for example, anycast sends to a single consumer, while multicast sends to all consumers).
- Window functions like Hamming, Hann, or Blackman are applied to signal segments to gradually reduce their values toward zero at the boundaries. By softening these abrupt edges, they prevent sudden jumps in the signal that would lead to spectral leakage and a loss of accuracy in the frequency domain.
- Parallel SAD calculation is a technique where multiple Sum of Absolute Differences computations are performed at the same time instead of sequentially, to speed up processing.
- SAD itself measures the difference between two signals or blocks (commonly image or video blocks) by summing the absolute value of element-wise differences:
- Advanced Transistor Structures (Fin FET and GAA):
- Modern semiconductor nodes have moved away from traditional planar MOSFETs toward Fin FET and Gate-All-Around designs. These architectures offer stronger gate control over the channel, significantly lowering leakage currents while boosting switching performance.
- 3D Integrated Circuits and Heterogeneous Integration:
- As traditional 2D scaling reaches its limits, vertical integration stacks multiple circuit layers using techniques such as through-silicon vias (TSVs) and wafer bonding. This shortens interconnect paths, reduces delay, and improves overall system performance.
  - Next-Generation Materials Beyond Silicon:
  - Emerging materials like graphene, carbon nanotubes, and two-dimensional semiconductors (such as MoS_2) are being explored for their superior carrier mobility, improved heat handling, and potential for higher-speed operation compared to silicon.
  - Extreme Ultraviolet (EUV) Lithography:
- EUV lithography enables highly precise patterning at extremely small technology nodes (below 7 nm), making it possible to pack more transistors onto a chip with improved accuracy.
  - Ultra-Low Power Design Techniques:
- Advanced VLSI systems focus heavily on power efficiency through methods such as voltage scaling, power gating, and energy-aware architectures, which are essential for IoT devices, wearables, and other battery-powered applications.
  - AI- and ML-Based Design Automation:
- Modern EDA tools leverage artificial intelligence and machine learning to optimize tasks like placement, routing, and floorplanning, accelerating design cycles and improving design quality.
  - In-Memory Computing and Emerging Memory Technologies:
- To address data transfer bottlenecks, computation is increasingly performed closer to memory. Technologies such as RRAM, PCM, and MRAM provide fast, non-volatile storage that enables efficient in-memory processing.

DOI 10.5281/zenodo.19500630

- Harnessing Quantum Effects:
- Instead of merely minimizing quantum phenomena like tunneling, advanced devices take advantage of them through approaches such as Tunnel FETs and Quantum Dot Cellular Automata, enabling more energy-efficient computation.
- Neuromorphic Computing Architectures:
- These systems mimic the structure and behavior of the human brain by using spiking neural networks, offering highly efficient processing for AI and cognitive computing tasks.
- Furthermore, advances in lithography technologies, particularly Extreme Ultraviolet (EUV) lithography, have enabled the fabrication of transistors at sub-7 nm nodes with greater precision and reduced patterning complexity. This has played a crucial role in continuing device miniaturization despite increasing fabrication challenges.
- Another emerging trend is in-memory computing, which reduces the data transfer bottleneck between processor and memory by performing computation directly within memory arrays. Technologies such as Resistive RAM (RRAM), Phase Change Memory (PCM), and Magnetoresistive RAM (MRAM) are gaining attention for enabling faster and more energy-efficient processing.
- In addition, interconnect innovation is becoming equally important as transistor scaling. As device dimensions shrink, interconnect delay and power consumption dominate system performance, leading to the exploration of alternative materials, optical interconnects, and advanced routing techniques.

II. PIN DAIGRAM

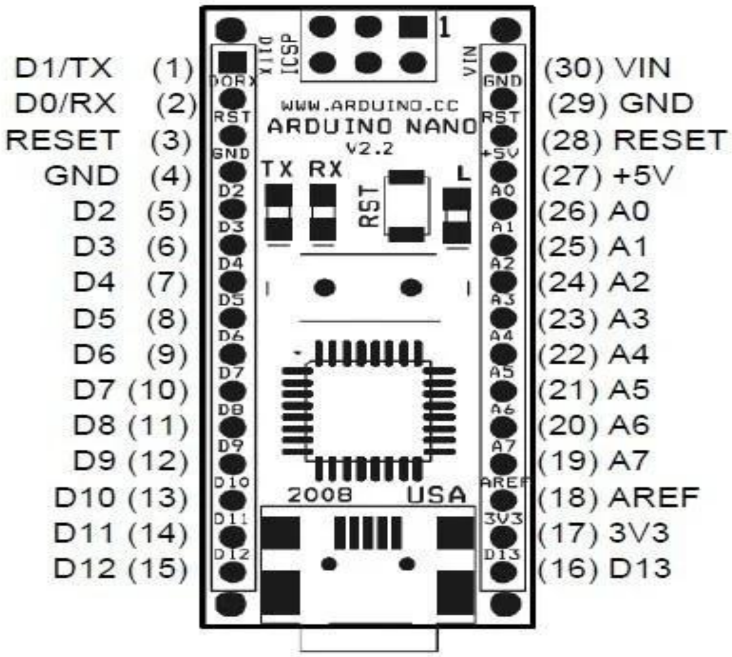

Figure 2: PIN DESCRIPTONS

- VIN (Pin 30): Used to supply power from an external source when USB is not used. The recommended input voltage is between 7V and 12V.
- 5V (Pin 27): Outputs a regulated 5V supply from the onboard voltage regulator.
- 3V3 (Pin 17): Provides a regulated 3.3V output generated internally.
- GND (Pins 4, 29, and others): Ground reference pins for the circuit.
- Digital Input/Output Pins
- The board features 14 digital I/O pins, labeled D0 to D13.
- These pins operate at 5V and can source or sink up to 40mA of current.
- PWM Capability: Pins 3, 5, 6, 9, 10, and 11 support Pulse Width Modulation.
- External Interrupts: Pins 2 and 3 can be configured to trigger external interrupts.
- Onboard LED: A built-in LED is connected to pin 13 for basic output indication.
- Analog Input Pins
- There are 8 analog input pins labeled A0 to A7.
- They can read voltages from 0 to 5V using a 10-bit analog-to-digital converter (ADC).
- Pins A0 to A5 may also be used as digital I/O pins.
- AREF (Pin 18): Allows an external reference voltage to be applied for analog measurements.
- Communication Interfaces
- The Nano supports several communication standards:
- UART (Serial):
    - D0 (RX): Receives serial data
    - D1 (TX): Transmits serial data
    - I2C (TWI):
    - A4: SDA (data line)
    - A5: SCL (clock line)
- SPI:
    - Pin 10: SS
    - Pin 11: MOSI
    - Pin 12: MISO
    - Pin 13: SCK
    - Reset Pins
- The board includes two reset pins (Pins 3 and 28). These are active-low and are used to reset the microcontroller

III. ADVANTAGES

1. **Higher Performance and Speed:**
    - Faster Switching: Modern transistors like Fin FETs and Gate-All-Around (GAA) FETs have very short channels, enabling them to turn on and off more quickly. This allows processors to run at higher clock speeds.
    - Lower Parasitic Effects: Smaller component spacing reduces unwanted capacitance,

DOI 10.5281/zenodo.19500630

shortening signal travel time and improving overall system responsiveness.

- High-Bandwidth Memory: Technologies such as 3D integrated circuits and advanced chip packaging improve data transfer speeds between processors and memory, which is especially important for AI and high-performance computing workloads.

2. **Greater Miniaturization and Integration:**
   - Higher Transistor Density: Nano-scale electronics make it possible to place billions of transistors on a single chip, enabling more powerful and sophisticated circuits.
   - System-on-Chip Integration: Increased density allows processors, memory, and peripherals to coexist on one chip, supporting compact designs for smartphones, wearables, and IoT.
   - Smaller Chip Size: Reduced component dimensions lead to smaller, lighter chips, benefiting portable and embedded systems.

3. **Improved Energy Efficiency:**
   - Reduced Power Usage: Lower operating voltages and smaller capacitances significantly cut power consumption, extending battery life and lowering energy demands in data centers.
   - Less Leakage Current: Advanced transistor designs provide better control over electrical flow, minimizing energy loss seen in older planar transistors.
   - Approximate Computing: Some nano-scale architectures intentionally relax accuracy to achieve major energy savings, particularly useful in AI and machine learning applications.

4. **Expanded Capabilities and New Technologies:**
   - Innovative Materials: Materials such as graphene, carbon nanotubes, and other 2D materials offer improved conductivity, flexibility, and performance beyond traditional silicon.
   - Neuromorphic Systems: Devices like memristors and non-volatile memories (ReRAM, MRAM support brain-inspired computing models that are highly efficient for AI tasks.
   - Advanced Sensing: Nano-scale sensors provide exceptional sensitivity, enabling precise detection of chemical and biological signals for healthcare and IoT applications.

5. **Conomic and Strategic Advantages:**
   - Lower Cost per Function: Although fabrication is costly, integrating more features into a smaller chip area reduces the cost per transistor and overall system cost.
   - Better Yield and Reliability: AI-assisted design tools and advanced manufacturing processes improve production efficiency, thermal control, and long-term chip reliability.
   - Reduced Power Usage: Lower operating voltages and smaller capacitances significantly cut power consumption, extending battery life and lowering energy demands in data centers.
   - Less Leakage Current: Advanced transistor designs provide better control over electrical flow, minimizing energy loss seen in older planar transistors.
   - Approximate Computing: Some nano-scale architectures intentionally relax accuracy to achieve major energy savings, particularly useful in AI and machine learning applications.

DOI 10.5281/zenodo.19500630

6. **Expanded Capabilities and New Technologies:**
   - Innovative Materials: Materials such as graphene, carbon nanotubes, and other 2D materials offer improved conductivity, flexibility, and performance beyond traditional silicon.
   - Neuromorphic Systems: Devices like memristors and non-volatile memories (ReRAM, MRAM) support brain-inspired computing models that are highly efficient for AI tasks.
   - Advanced Sensing: Nano-scale sensors provide exceptional sensitivity, enabling precise detection of chemical and biological signals for healthcare and IoT applications.

7. **Economic and Strategic Advantages:**
   - Lower Cost per Function: Although fabrication is costly, integrating more features into a smaller chip area reduces the cost per transistor and overall system cost.
   - Better Yield and Reliability: AI-assisted design tools and advanced manufacturing processes improve production efficiency, thermal control, and long-term chip reliability.

IV. APPLICATONS

1. **AI/ML Hardware Accelerators:**
   - Implementation of dedicated AI chips (neuromorphic computing) utilizing memristors for in-memory computing to reduce power consumption and increase processing speed for neural networks.
   - Heterogeneous Integration & 3D ICs: Combining different technologies (memory, logic, MEMS) on a single chip to enhance functionality and reduce latency, moving beyond traditional 2D planar scaling.
   - Advanced Transistor Architectures: Adoption of FinFETs, Gate-All-Around (GAA) FETs, and Nanowire transistors to maintain electrostatic control and reduce leakage current at advanced nodes.

2. **Communication and Connectivity (5G/6G):**
   - RFIC/MMIC Design: Advanced Radio Frequency Integrated Circuits (RFICs) using wide-bandgap materials for 5G/6G, enabling faster data rates and lower latency.
   - Nano-photonic Integration: Using light-based technologies on-chip to revolutionize data transmission speeds.

3. **Healthcare and Biomedical Devices:**
   - Implantable & Wearable Sensors: Nano-enabled biosensors and lab-on-a-chip devices for real-time, point-of-care diagnostics, and continuous health monitoring.
   - Neural Interfaces: High-density, low-power circuits that interface directly with neural systems for therapeutic stimulation.

DOI 10.5281/zenodo.19500630

4. **Internet of Things (IoT) and Low-Power Electronics:**
    - Ultra-Low Power Systems: Development of energy-scavenged, autonomous devices that consume minimal power, ideal for ambient intelligence and remote sensing.
    - Carbon Nanotube Field-Effect Transistors (CNTFETs): Utilized for designing 32nm and smaller digital building blocks that offer superior power-delay products compared to silicon.

5. **Emerging Materials and Computing Paradigms:**
    - 2D Material Devices: Research into graphene, MoS_2, and MXENES for flexible electronics and next-generation, high-speed transistors.
    - Spintronics: Using the spin of electrons for data storage and processing, providing potential for non-volatile, ultra-low-power memory.
    - Quantum Computing Components: Development and control circuits for qubits (quantum dots, superconducting circuits) to achieve revolutionary computational speeds.

V. CONCLUSION

In addition to these developments, interconnect scaling has emerged as a critical bottleneck, as resistance–capacitance (RC) delays increasingly dominate overall circuit performance at nanoscale dimensions. To address this, novel interconnect materials, low-k dielectrics, and advanced packaging techniques such as 2.5D integration and silicon interposers are being explored. Furthermore, design complexity has grown significantly, necessitating the use of advanced electronic design automation (EDA) tools, often enhanced with artificial intelligence and machine learning, to optimize layout, power, and timing in highly integrated systems.

Another important trend is the rise of heterogeneous integration, where multiple specialized processing units such as CPUs, GPUs, and AI accelerators are combined within a single system to improve efficiency for specific workloads. This shift is closely tied to the increasing importance of data-centric and edge computing applications, where low latency and energy efficiency are critical. Additionally, hardware security has become a major concern, leading to the incorporation of secure design practices to protect against threats such as hardware Trojans and side-channel attacks.

From a manufacturing perspective, variability and yield challenges at advanced technology nodes require innovative fabrication techniques, improved process control, and design-for-manufacturability (DFM) methodologies. At the same time, sustainability considerations, including energy-efficient computing and environmentally responsible fabrication processes, are gaining importance in the semiconductor industry.

Looking ahead, emerging paradigms such as photonic computing, which utilizes light for high-speed data transmission, and bio-inspired electronics, including flexible and wearable devices, are expected to further expand the scope of nanoelectronics. Ultimately, the continued evolution of VLSI systems will depend not only on scaling and materials innovation but also on breakthroughs in system architecture, design methodologies, and cross-disciplinary collaboration to meet the growing demands of modern computing applications.

DOI 10.5281/zenodo.19500630

REFERENCES

[1] S. M. Sze and K. K. Ng, Physics of Semiconductor Devices, 3rd ed. Hoboken, NJ: Wiley-Interscience, 2007.

[2] N. H. E. Weste and D. M. Harris, CMOS VLSI Design: A Circuits and Systems Perspective, 4th ed. Boston, MA: Addison-Wesley, 2011.

[3] S. P. Mohanty, Nano-Electronic Mixed-Signal System Design. New York, NY: McGraw-Hill Education, 2015.

[4] N. K. Jha and R. Dhiman, Nanoelectronics: Devices, Circuits and Systems (Micro & Nano Technologies Series). Amsterdam: Elsevier, 2022.

[5] C. Auth et al., "A 10nm high performance and low-power CMOS technology featuring 3rd generation FinFET transistors, Self-Aligned Quad Patterning, contact over active gate and cobalt local interconnects," in Proc. IEEE IEDM, San Francisco, CA, 2017, pp. 29.1.1–29.1.3.

[6] H.-S. P. Wong, S. Akarvardar, D. Antoniadis, J. Bokor, C. Hu, T.-J. King, et al., "A density metric for semiconductor technology," Proceedings of the IEEE, vol. 108, no. 4, pp. 478–482, Apr. 2020.

[7] M. Lapedus, "EUV Lithography Finally Ready for Volume Production," Semiconductor Engineering, 2019. [Online]. Available: https://semiengineering.com

[8] P. Batude et al., "3D sequential integration: A key enabling technology for heterogeneous co-integration of new function with CMOS," IEEE Journal on Emerging and Selected Topics in Circuits and Systems, vol. 2, no. 4, pp. 714–722, Dec. 2012.

[9] A. K. Geim and K. S. Novoselov, "The rise of graphene," Nature Materials, vol. 6, no. 3, pp. 183–191, Mar. 2007.

[10] B. Radisavljevic, A. Radenovic, J. Brivio, V. Giacometti, and A. Kis, "Single-layer MoS_2 transistors," Nature Nanotechnology, vol. 6, no. 3, pp. 147–150, Mar. 2011.

[11] G. Indiveri et al., "Neuromorphic silicon neuron circuits," Frontiers in Neuroscience, vol. 5, article 73, May 2011.

[12] A. Chen, "A review of emerging non-volatile memory (NVM) technologies and applications," Solid-State Electronics, vol. 125, pp. 25–38, Nov. 2016.

[13] Nanoelectronics: Devices, Circuits and Systems (Micro & Nano Technologies) by Niraj K. Jha and Rohit Dhiman (2022/2023)

[14] Nano-electronic Mixed-Signal System Design by Saraju P. Mohanty (2015)

[15] CMOS VLSI Design: A Circuits and Systems Perspective by Neil H. E. Weste & David Harris

DOI 10.5281/zenodo.19500630