# Digital Twins for Semiconductors

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# Agenda

- About me
- Digital Twins: The Concept
- Why Semiconductors Need Digital Twins
- The Architecture of Semiconductor Digital Twins
- AI's Transformative Role
- Real-World Case Studies
- Future Directions
- Q&A

# About Me

- An Phan, AI Solutions Engineer at Aitomatic (2021-2025)
- 12+ years in data engineering with focus on AI engineering for physical systems including transportation (2012-2015), connected devices (2015-2016), manufacturing (2018-2024), maritime (2022-2025), and semiconductors (2024-2025)
- Co-author of published papers: SemiKong (Semiconductor Industry-Specific LLM - Nov 2024), Llamarine (Maritime Industry-Specific LLM - Feb 2025)
- Passionate about bridging digital AI and physical AI

# My Journey: Bridging Digital and Physical Worlds

### First lesson (2014)

- As a junior software engineer, changed password requirement from 8 to 16 characters, "Just one LOC, what's the big deal?"
- Manager showed stack of paperwork: security compliance documents, token device manufacturer updates
- 1st lesson: "One small change in the digital world can create major ripples in the physical world"

### Manufacturing Transformation at Panasonic (2018-2023)

- Challenge: Convincing factory floor experts to trust AI predictions
- Built predictive maintenance system for production equipment
- Key insight: "AI isn't replacing human expertise; it's extending human capabilities"

### Maritime Challenge (2024-2025)

- Collision avoidance requires real-time decision making
- Developed Llamarine LLM to understand maritime domain knowledge

### Semiconductors Challenge (2024-2025)

- Similar patterns: Complex physical systems with many variables
- Different constraints: Higher precision, lower tolerance for errors
- Using domain-specific LLMs to understand the highly specialized semiconductor language

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# Digital Twins: The Concept

**Definition**: Virtual replicas of physical assets, processes, or systems

**Purpose**: Real-time monitoring, simulation, optimization, and prediction

**Evolution**: From CAD models → simulation models → intelligent, adaptive twins

**Key Components**:

- Physical entity
- Virtual entity
- Data connections
- AI/ML models
- Visualization layer

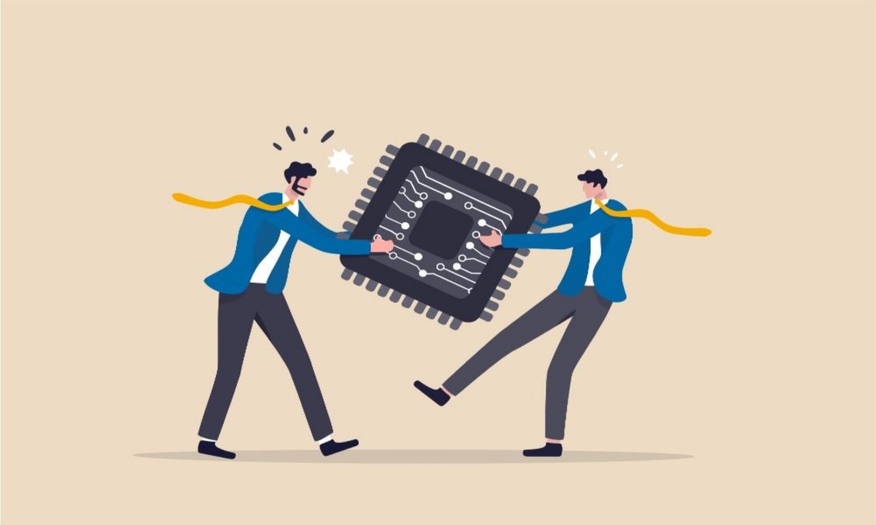
# Why Semiconductors Need Digital Twins

## The Challenge

- Semiconductor manufacturing: 300-800 process steps, often across multiple facilities
- **Complexity** increasing with each node (5nm → 3nm → 2nm)
- **Fab construction costs**: $10-20 billion per facility (TSMC's Arizona fab estimated at $40 billion)
- Average **fab downtime cost**: $2.8 million per hour
- **Yield impact**: 1% yield improvement can mean $10-20 million in annual savings for a large fab

## Without Digital Twins

- Reactive maintenance (not predictive)
- Trial-and-error process optimization
- Limited visibility across the value chain
- Slower innovation cycles
- Higher failure rates



# The Architecture of Semiconductor Digital Twins

**Layers of Implementation**

1. **Device Level**: Individual equipment monitoring
   - Etchers, CVD tools, lithography scanners
   - Real-time performance tracking
2. **Process Level**: Manufacturing sequences
   - Recipe parameters
   - Process windows
   - Material flow
3. **Fab Level**: Entire production facility
   - Tool interdependencies
   - Workflow optimization
   - Resource allocation
4. **Supply Chain Level**: End-to-end visibility
   - Material tracking
   - Supplier integration
   - Demand forecasting

# AI's Transformative Role

## From Descriptive to Prescriptive Analytics

1. **Monitoring** → What is happening?
2. **Diagnostics** → Why did it happen?
3. **Predictive** → What will happen?
4. **Prescriptive** → What should we do?

## AI Techniques in Semiconductor Digital Twins

- **Computer Vision**: Wafer defect classification, Photomask inspection and verification, etc.
- **Time Series Analysis**: Equipment degradation prediction, Chamber matching across multiple tools, etc.
- **Natural Language Processing**: Knowledge extraction from maintenance logs, Standard operating procedure generation, Failure analysis assistance, Capturing tribal knowledge from retiring experts, etc.
- **Reinforcement Learning**: Process recipe optimization, Scheduling optimization for multiple products, etc.

# Case Study: Process Optimization at Fab

**Challenge**

- Complex etch process with multiple variables
- Traditional modeling couldn't capture all interdependencies
- Engineers spending 40+ hours/week troubleshooting

**Digital Twin Solution**

- Sensors collecting 500+ parameters per minute
- Deep learning models to predict process outcomes
- What-if simulation capability

**Results**

- Reduction in process development time
- Improvement in first-time-right production

# Case Study: Virtual Fab

## Implementation Overview

- Comprehensive "Virtual Fab" concept across multiple facilities
- Integration of equipment, process, and facility digital twins
- Physics-based models enhanced with AI learning capabilities
- Focus on closed-loop control and autonomous decision-making

## Results

- Reduction in process variation
- Improvement in overall equipment effectiveness
- Faster time-to-yield for new processes

# The Challenges

### Technical Challenges

- Data quality and consistency across legacy equipment
- Real-time processing of massive sensor data
- Model drift in dynamic manufacturing environments

### Human Challenges

- Domain expertise translation into AI systems
- Engineering acceptance of AI recommendations
- Balancing automation with human oversight

The hardest part isn't building the technology; it's building the trust.

# SemiKong: Our Industry-Specific Initial Approach

Semiconductor-specific LLM published in 2024

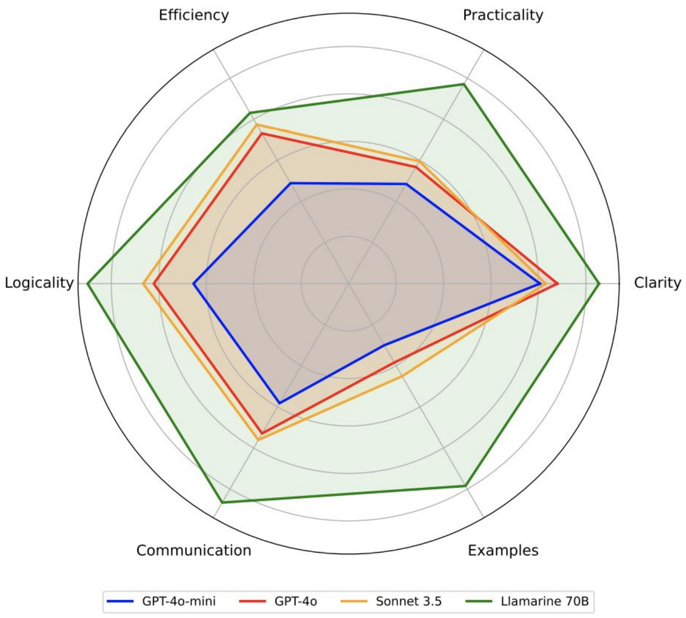
Training dataset included:

- Technical literature from IEEE, ACM, and semiconductor conferences
- Public semiconductor patents
- Industry standards and specifications
- Carefully curated and anonymized troubleshooting sessions

Knowledge coverage spanning device physics, process technology, equipment maintenance, and yield analysis

Results:

- Enables semantic understanding of equipment behavior patterns
- Foundation for more intuitive digital twin interactions



# Future Directions

### Autonomous Fabs

- Continuous process optimization
- Dynamic scheduling based on real-time conditions

### Extended Reality Integration

- AR overlays for maintenance technicians
- VR training and scenario planning
- Digital twin visualization beyond dashboards

### Knowledge Democratization

- Making expert knowledge accessible through AI
- Breaking down silos between design and manufacturing
- Preserving institutional knowledge

# Key Takeaways

- Digital twins move semiconductor manufacturing from reactive to predictive
- AI is the key differentiator between simulation and true digital twins
- Domain-specific understanding is critical to success
- The human-AI interface remains the biggest challenge and opportunity
- The future belongs to those who can seamlessly integrate physical and digital worlds

*Digital twins aren't just about modeling what is; they're about revealing what could be.*

# Thank You!

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