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Automation systems and integration — Digital twin framework for manufacturing~~ — ~~—

Part 100:
Use case on management of semiconductor ingot growth process

~~DTR stage~~

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This document was prepared by Technical Committee ISO/TC 184, *Automation systems and integration*, Subcommittee SC 4, *Industrial data*.

A list of all parts in the ISO 23247 series can be found on the ISO website.

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Introduction

The semiconductor ingot growing process is an important step in the production of semiconductor wafers, which are used to manufacture electronic components such as integrated circuits and solar cells.

Despite advancements in automated ingot growth equipment, the conventional ingot growth process continues to face challenges due to the degree of human intervention required, it often relies on operators' experience and know-how. This dependence can lead to issues such as inaccurate quality, inconsistent machine setup, unstable temperature maintenance, and inconsistent melting.

A digital twin for the ingot growth process can effectively address these issues by simulating and optimizing the entire process in a virtual environment and reducing reliance on manual intervention.

Using a digital twin for monitoring and controlling the ingot growth process offers several advantages as follows:

- Real-time monitoring: a digital twin allows continuous and real-time monitoring of the ingot growth process. It provides detailed insights into key parameters such as temperature, growth rate, crystal quality, and dopant concentration. This enables operators to detect deviations or anomalies early on and take necessary corrective actions promptly.

- Process optimization: by analysing the data collected for the digital twin, it becomes possible to optimize the ingot growth process. Patterns and trends can be identified, allowing for adjustments in various parameters to improve yield, reduce defects~~,~~ and enhance the overall quality of the ingots and resulting wafers.

- Predictive maintenance: a digital twin can help predict maintenance requirements for the equipment used in the ingot growth process. By monitoring equipment performance and analysing historical data, the digital twin can help identify potential issues or deterioration in advance, enabling proactive maintenance and minimizing unplanned downtime.

- Training and simulation: a digital twin can be used for training operators and engineers. It provides a virtual environment where individuals can practice and simulate different scenarios without the need for actual physical equipment. This helps in enhancing operational skills, testing new strategies, and improving decision-making capabilities.

By leveraging the advantages of a digital twin, semiconductor manufacturers can gain deeper insights into the ingot growth process, optimize production parameters, enhance quality control, and improve overall productivity and efficiency.

Automation systems and integration — Digital twin framework for manufacturing~~ —~~ —

Part 100:
Use case on management of semiconductor ingot growth process

1 Scope

This document describes a digital twin for monitoring and controlling the semiconductor ingot growth process. The use case is analysed and designed using the ISO 23247~~, "Digital twin framework for manufacturing".~~ series. The result is a systematic view of the use case implementation and a high-level design of the digital twins, which can be directly implemented using the readily available tools and languages, including those supported by the relevant standards.

2 Normative references

~~There are no normative references in this document.~~

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 23247-1, *Automation systems and integration — Digital twin framework for manufacturing — Part 1: Overview and general principles*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 23247-1 and the following apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

3.1 ~~3.1~~

ingot
large, single crystal of semiconductor material, typically silicon, that serves as the starting material for the production of semiconductor wafers

Note 1 to entry: The ingot is grown through a process called ingot growth, where high-purity silicon is melted and then slowly solidified to form a large cylindrical crystal. This crystal is typically several inches in diameter and can be several feet long, depending on the intended use and requirements.

Note 2 to entry: The ingot is the primary raw material from which individual semiconductor wafers are cut. These wafers undergo further processing steps to fabricate electronic components such as integrated circuits (ICs) or solar cells. The quality and characteristics of the ingot, including its crystalline structure and impurity levels, play a crucial role in determining the performance and reliability of the resulting semiconductor devices.

3.2 ~~3.2~~

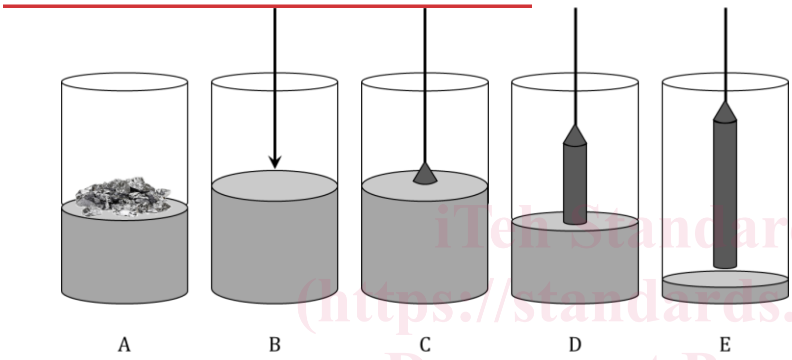
ingot growth process
crystal growth process
step in semiconductor manufacturing where high-purity silicon is melted to grow a crystal

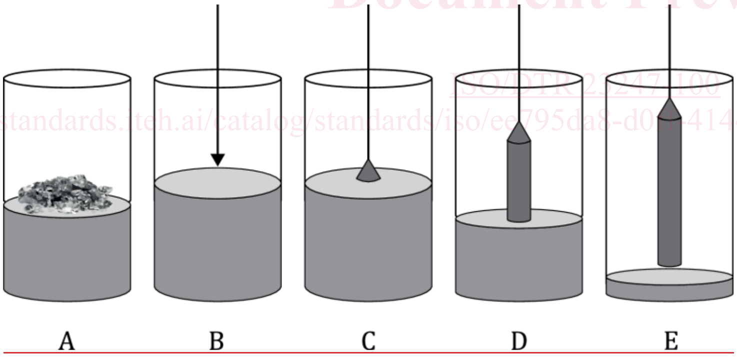
Note 1 to entry: In this process, a small single crystal called a “seed crystal” is carefully placed on molten silicon, and as the seed crystal is slowly withdrawn, silicon atoms from the molten phase arrange themselves in an ordered lattice structure, forming a larger crystal.

Note 2 to entry: The growth is controlled by parameters such as temperature and pulling rate, resulting in the uniform and high-quality growth of the silicon crystal. The grown crystal is then used to produce semiconductor wafers.

4 Overview

The semiconductor ingot growth process is an important step in semiconductor wafer production. Figure 1 presents the conventional procedures of the ingot growth process.





Key

A	melting of polysilicon, doping
B	introduction of the seed crystal
C	beginning of the crystal growth
D	crystal pulling
E	formed crystal with a residue of melted silicon

Deleted Cells

Deleted Cells

Figure 1 — Ingot growth process

The conventional procedures of the ingot growth process are as follows:

1. ~~Material selection: High-purity silicon is chosen as the starting material due to its desirable semiconductor properties. The silicon is typically sourced in the form of polysilicon or as metallurgical-grade silicon.~~
2. ~~Preparation of the crystal growth equipment: The equipment used for crystal growth, such as a furnace, is cleaned and prepared before the ingot growth process begins.~~
3. ~~Melting: The silicon is melted in a high-temperature furnace, usually by using a radiofrequency (RF) induction heating system. The crucible used for melting is often made of quartz or graphite, which can withstand extreme heat.~~
4. ~~Dopant addition: During the melting process, certain impurities or dopants such as boron, phosphorus, or arsenic can be intentionally added to the molten silicon to alter its electrical properties. This allows the resulting wafers to have specific conductivity characteristics. By precisely controlling the doping process, manufacturers can tailor the silicon ingots to meet specific conductivity requirements for different applications, such as integrated circuits (ICs) or solar cells.~~
5. ~~Seeding the crystal: A small single crystal of the same material, called a seed crystal, is carefully placed on top of the molten semiconductor material. The seed crystal serves as a starting point for the growth of a larger crystal.~~
6. ~~Crystal growth: The seed crystal is immersed into the molten silicon and slowly withdrawn at a controlled rate. As the seed is pulled, silicon atoms from the molten phase begin to arrange themselves in an ordered lattice structure, mirroring the crystal orientation of the seed.~~
7. ~~Ingot pulling: The seed crystal is slowly pulled out of the molten semiconductor material. As it is pulled, the semiconductor material solidifies and forms a single crystal structure around the seed crystal. The rate of pulling, temperature control, and other parameters are carefully controlled to ensure uniformity and quality.~~
8. ~~Testing and inspection: The ingot is carefully inspected and tested to ensure that it meets the required quality standards. Any defects or impurities must be identified and addressed before the ingot can be used to manufacture semiconductor wafers.~~

Despite advancements in automated ingot growth equipment, the conventional ingot growth process continues to face challenges due to the degree of human intervention required, the process often relies on operators' experience and know-how. This dependence can lead to issues such as inaccurate material quality, inconsistent machine setup, unstable temperature maintenance~~,~~ and inconsistent melting.

A digital twin for the ingot growth process can effectively address these issues by simulating and optimizing the entire process in a virtual environment. Using a digital twin enables predictive modeling and real-time adjustments that enhance quality control and process stability.

Furthermore, by reducing reliance on manual intervention, digital twins facilitate a more consistent application of best practices and compliance with industry standards, ultimately leading to improved efficiency and reduced operational costs.

Table 1 summarizes the drawbacks and advantages of the conventional ingot growth process and the solutions offered by a digital twin.

Table 1 — Comparison of conventional ingot growth process and digital twin solutions

Stages of ingot growth process	**Drawbacks of the conventional method**	**Solutions by digital twin**	**Advantages of the digital twin solution**
Material selection	Dependence on human judgment for material quality	Automated material quality check using sensors and AI algorithms	Increased accuracy in material quality and reduced reliance on human judgment

Stages of ingot growth process	**Drawbacks of the conventional method**	**Solutions by digital twin**	**Advantages of the digital twin solution**
Preparation of equipment	Manual cleaning and preparation can miss inconsistencies	Real-time monitoring and feedback for equipment preparation	Consistent equipment setup leading to standardized outcomes
Melting	Fluctuating temperature and inconsistent melting	Real-time temperature monitoring and AI-based adjustments	Stable and consistent melting process
Dopant addition	Inaccurate dopant concentrations due to manual operations	Precision-controlled dopant addition using feedback loops	Precise and consistent doping levels
Seeding the crystal	Potential misalignment of the seed crystal	Automated alignment with feedback systems	Perfect seed alignment, leading to better crystal quality
Crystal growth	Variability in growth rate and potential defects	AI-controlled growth rate based on real-time feedback	Consistent growth rate, reduced defects
Ingot pulling	Reliance on operator skill for pulling rate and parameters	Automated pulling with consistent parameters	Uniformity and quality of ingots
Testing and inspection	Manual inspection can miss subtle defects	Automated inspection using machine vision and AI	Higher defect detection rate and consistency

Integrating a digital twin into the ingot growth process can bring significant advantages and resolve challenges associated with conventional methodologies. It offers a more data-driven, predictive, and optimized approach, leading to better outcomes in terms of quality, efficiency, and safety.

Table 2 describes the use case for the management of the semiconductor ingot growth process using a use case template given by ~~Annex B of~~ ISO 23247-4:2021, Annex B.

Table 2 — Summary of the example for the management of the semiconductor ingot growth process

ID	Case ~~Number~~number 100
Use case name	Management of the semiconductor ingot growth process
Application field	Smart ~~Manufacturing~~manufacturing
Life cycle stage(s)/phase(s) coverage	Production
Status	In-operation
Scope	Automated manufacturing process adjustment and tracking based on variable conditions of the ingot growth equipment (i.e~~.,~~. furnace)
Initial (~~Problem~~problem) Situation	The ingot pulling process, the rate of pulling, temperature control~~,~~ and other parameters are carefully controlled to ensure uniformity and quality. This can be done by operator experience, process monitoring, feedback control system~~,~~ and closed-loop control system.
Objective(s)	Production of ingot ensuring uniformity and quality
-	Developing a digital twin of the ingot growth process can provide the following: