Holland High Tech Roadmap

Semiconductor Manufacturing Equipment

2024 - 2027

Version 3.0 | January 15, 2024 | PUBLIC

Holland High Tech
Global Challenges, Smart Solutions

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Contents

1. Societal challenges and economic relevance

1.1. Societal challenges addressed in this roadmap

Semiconductor technology and its role in the creation of electronic components and systems is an essential enabler for solving the major societal challenges, like the climate- and energy crisis, digitalization and circularity in all sectors. Moreover, fueled by geopolitical tension, there is also the challenge of deglobalization to consider, calling for greater strategic autonomy and securing of supply chains. As such it is of prime strategic importance to defend and strengthen the Dutch position in the semiconductor value chain.

The traditionally strong position in semiconductor manufacturing equipment can be further strengthened and grown through diversification by enabling innovation and leveraging Dutch core competences. This will safeguard the future security of supply and strengthen a flourishing economic sector for the Netherlands.

The central role of semiconductors in solving societal challenges

The semiconductor equipment sector drives significant innovations for Electronic Components and Systems with more/other functionality and more embedded electronic computing power. The sector does this in two main ways.

First, it drives the need for more computing power and higher energy efficiency by driving Moore’s law: more transistors – computing power- on the same chip area. This enables high-end computing needs like massive data centers with High Performance Computers for Cloud Computing, mobile devices with a high degree of functionality and internet-of-things devices. Furthermore, the sector drives innovations in the More than Moore area: combining different chiplets, platforms and functionality in one device.

Second, these innovations are at the heart of the digital transition, driving the possibilities of AI and connectivity. Also, the transitions to a circular economy and an economy based on renewable energy will critically depend on Electronic components and systems and digitalization. Mobility will be powered by smart vehicles with integrated sensors and computing power, the energy grid needs smart adaptations and for a circular economy a high degree of digital tracking will be indispensable.

Economic opportunities in a changing context

This changing context creates opportunities for the Dutch semiconductor equipment sector. Reshoring manufacturing, packaging and testing to Europe and North America increases the total market size for equipment in a significant way. Moreover, reshoring also drives demand for more cost-effective, i.e. less labor intensive, far-reaching automation and digitalization.

Security of supply and open[1] strategic autonomy

Semiconductor value chains are known for their complexity. The high pace of innovation, capital- and knowledge intensity and diversity in requirements for individual steps have over the past decades led to a highly economically efficient and global industry. Moreover, the pace of innovation and the efficiency improvement have enabled the far-reaching societal benefits of affordable digitalization.

Some of the individual steps within the value chain are so capital- and/or knowledge intensive that only a single company, like for example ASML, for lithography, ASM for Atomic Layer Deposition, KLA-Tencor for inspection and Tokyo Electron for tracks, can provide the highest level of technology. The unique knowledge positions of these companies lead to strong interdependencies, between companies and states. These interdependencies pose risks on the security of supply to downstream industries and consumers. A changing geopolitical context further compounds these risks. Dependency on third countries for essential chip technology leads to the societal demand for increased security of supply.

For a small country such as the Netherlands, and even for Europe, full autonomy is not obtainable, or practical. Therefore, strategic autonomy and an increased security of supply should be addressed in the light of the complexity of value chains and interdependencies. A strategy of maximizing the quantity and quality of unique knowledge positions, if not control points, within in the value chain is viable. This strategy should include the preservation of existing control points, and the development of novel control points in emerging technologies and capabilities. Herein, technological leadership is key.

1.2. World-wide market for this roadmap, now and in 2027

1.2.1. Market for Semiconductor Manufacturing Equipment

In this roadmap the semiconductor manufacturing equipment market has been split into 3 domains, “Wafer-Fab Equipment”, “Assembly Equipment” and “Test Equipment”. Based on the May 2023 market numbers from TechInsights[2], the world market for Semiconductor Manufacturing Equipment is as indicated in Table 1. The maximum addressable market for Wafer-Fab equipment in 2022 is by far the largest segment of the total market (in NL addressed by e.g., ASML, ASM, Thermo Fisher Scientific and Nearfield Instruments with their ecosystems), followed by Test Equipment which is a factor 12 smaller (without major Dutch players), and by Assembly Equipment (factor 20 smaller, in NL addressed by e.g., Besi, ITEC, Boschman and Sempro).

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[1] "Open strategic autonomy" is the policy choice of NL (and Europe): https://open.overheid.nl/documenten/ronl-5b134a1ba15379fdfc6ecb0b6dcc431843087193/pdf

[2] TechInsights, May 2023

<table>
<tr><th colspan="3">Semiconductor Manufacturing Equipment
2022: $111.5B
2027: $146.7B</th></tr>
<tr><td>Wafer-Fab Equipment
2022: $97.7B (87.6%)
2027: $129.4B</td><td>Assembly Equipment
2022: $5.0B (5.0%)
2027: $7.0B</td><td>Test Equipment
2022: $8.2B (7.4%)
2027: $10.4B</td></tr>
</table>

Table 1: World Markets for Semiconductor Manufacturing Equipment[3]

Wafer-Fab Equipment

From the TechInsights report of May 2023 it further follows that, the world market for Wafer Fab Equipment consists of Cleaning & Etching Tools (28%), Deposition & Related Tools (27%), Lithographic & Mask Making Equipment (23%), Process Diagnostic Equipment (14%, including metrology and inspection), Chemical Mechanical Polishing Equipment (3%, Ion Implanters (2%), Other Equipment (3%).

Examples related to the Netherlands:

- ASML (with head office in Veldhoven) and its ecosystem of partners and suppliers, address the Lithographic Equipment and Process Diagnostic Equipment segments completing a Holistic Lithography workflow. Into the total Wafer-Fab Equipment market of $97.7B in 2022, ASML sold €21.2 billion (~$22.6 billion, which is about 1/4 of the addressable world market and includes a 100% market share for EUV (Extreme UV) Lithographic Scanners).[4] Besides EUV, there is DUV in which a capacity growth is expected of 2.5x to 600 systems/year in 2025-2026.
- ASM (with head office in Almere) sold into the total Wafer-Fab Equipment market €2.411 billion (~$2.6billion, so ~ 2.7% of the addressable world market share) in 2022.[5] ASM's Atomic Layer Deposition ("ALD") Product lines make the company a market leader in single wafer ALD, and enjoyed strong double-digit growth in 2022, with ALD continuing to represent more than half of the ASM equipment revenue. ASM's other product lines also contributed strongly, led by the Epitaxy product line. In 2022, ASM expanded into the high-growth market of silicon-carbide epitaxy.
- Thermo Fisher Scientific (head office in USA) has its main R&D, manufacturing and European Semiconductor customer application support "Nanoport" site for high-end Transmission Electron Microscopes ("TEM") in Eindhoven – established for over 50 years and the only high-end TEM R&D and manufacturing site outside north-east Asia. High-end TEM includes product lines specifically for the semiconductor market, in which Thermo Fisher Scientific is the market leader. It is worth noting that many high-end TEM innovations critical to the Semiconductor industry, result from initial R&D addressing needs in the Materials Science and Life Sciences TEM

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[3] TechInsights, May 2023

[4] https://www.asml.com/en/investors/annual-report/2022

[5] ASM International Annual Report 2022

markets – this high-end TEM innovation is also performed at the Thermo Fisher Scientific site in Eindhoven. The high-end TEM business of Thermo Fisher Scientific is a significant part of the Analytical Instruments Group, reporting a 2022 revenue approaching $7 Billion [6].

- The Dutch Semiconductor Manufacturing Equipment suppliers form vibrant ecosystems together with OEM module suppliers including VDL-ETG, NTS Group, Frencken, Demcon, Prodrive, Sioux and others. These OEM module suppliers also supply to other international Semiconductor Manufacturing Equipment companies. For example, system suppliers from the Dutch ecosystem support 7 out of the top-10 wafer fab equipment suppliers.
- On a smaller scale, Dutch mid-sized companies such as Tempress (Vaassen) and Trymax (Nijmegen) provide oxidation, deposition and etching solutions to semiconductor R&D institutes and mature node fabs. These fabs are important suppliers of semiconductor chips required for the electrification (high power/automotive) and low-cost connectivity.
- Nearfield Instruments (with head office in Rotterdam) delivers metrology & inspection solutions (equipment and software) for in-line, non-destructive semiconductor manufacturing process control, based on high-throughput atomic force microscopy (AFM). First product QUADRA, on-surface metrology is deployed in world-wide high-volume manufacturing, while the second product, AUDIRA enables non-destructive subsurface metrology applications. NFI closely works with partners in the Dutch high-tech supply chain and is strongly embedded in the EU semiconductor ecosystem (a.o. as the only Dutch SME as Direct Partner in IPCEI ME/CT).
- Solmates provides thin film Pulsed Laser Deposition (PLD) equipment. The diverse range of applications in Specialty Technologies requires the processing of novel materials. To address the challenging requirements of such materials, the very versatile PLD deposition technology is required to enable more advanced device design. In 2022 Solmates was acquired by Lam Research. Through this partnership the mass production of thin films for Specialty Technologies applications will be enabled.

Assembly Equipment

According to TechInsight, the world market for Assembly Equipment amounted in 2022 to $5.0B and consists of assembly inspection equipment, dicing, bonding, packaging and integrated assembly systems.

Examples related to the Netherlands:

- Besi (with head office in Duiven) sold €723 million.
- Other companies, like Boschman, Kulicke & Soffa (with headquarters in Singapore with part of its R&D in the Netherlands), ASMPT and ITEC.
- ITEC (with head office in Nijmegen) develops pick & place equipment to manufacture high volume, high precision, high quality, low cost and small dies (with spill-over to RFID, mini/micro-LED and wearable health diagnostics markets). ITEC is an independent company since 2021, which aims to grow its sales in Assembly and Test equipment to 150M€ in the next five years.

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[6] Thermo Fisher Scientific Inc. - Investors - Financials - Annual Reports

Test Equipment

According to TechInsights the world market for Test Equipment was in 2022 $8.2B and consists of Test and Measurement systems, handlers, and probers to optimize production of ICs for Memory, Logic, System-on-Chip, Micro Processors, Graphics Processors; Wireless Communications, etc.

Example related to the Netherlands:
This market is dominated by large players like Advantest (Headquarters in Japan) and Teradyne (Headquarters in the USA). VLSI research (listing threshold > ~ 0.1M$) does not list Test Equipment companies in the Netherlands with revenue from sales of Test Equipment. Though there are companies that aid in development of new Test Equipment and provide Test Services, such as Salland Engineering (Zwolle). Some Dutch companies also are intending to develop Test and Metrology tools for Photonic Integrated Circuits, like IMS (and partners), these products will start to come to market towards the end of 2024 or early 2025.

ITEC provides flexible automated equipment for final test and wafer test (discrete power and small signal) and automated optical inspection solutions. ITEC is an independent company since 2021, which aims to grow its sales in Assembly and Test equipment to 150M€ in the next five years.

Markets enabled by Semiconductor Manufacturing Equipment

The Semiconductor Manufacturing Equipment Industry enables many markets beyond its own, with a total value that, by far, exceeds the value of its own business going from Semiconductor Manufacturing Equipment to Chips to Electronics, see Figure 1, based on the 2022 numbers from TechInsights. Hence, continued innovations in semiconductor manufacturing equipment enable continued innovations in many, larger, markets.

Moreover, because the Semiconductor Manufacturing Equipment Industry is a front runner in several key technologies, like mechatronics and optics, this industry is an enabler for other high-tech industries and markets, creating spillovers in industries such as equipment for bio-medical (including life sciences) instrumentation, health, food, mobility, displays and other non-semiconductor high tech materials and components (including batteries) or space & astronomy instrumentation.

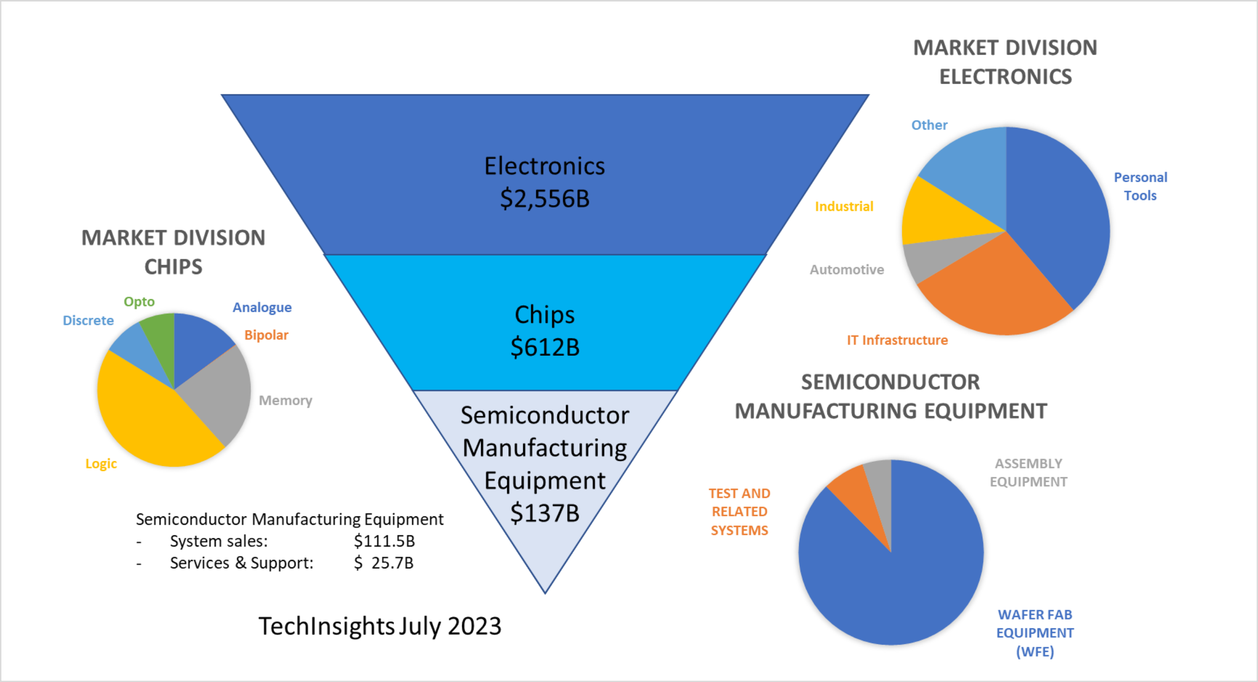


Figure 1. Markets enabled by Semiconductor Manufacturing Equipment, TechInsights July 2023.

1.3. Competitive position of the Dutch ecosystem (market and know-how)

In regard to the Dutch ecosystem:

- The Netherlands has a strong global position for Semiconductor Manufacturing Equipment. This has been quantified with examples in Section 1.2.1.
- (Almost) the whole supply chain is represented in The Netherlands from design, manufacturing (fab equipment like; wafer stepper/scanner, metrology, wafer fabs, assembly), testing & reliability.
- This strong global position is co-enabled by many Dutch OEM module suppliers, including VDL ETG, Demcon, ITEC, Neways, Salland Engineering, Sioux, Frencken, NTS Group and Prodrive.
- The strong global position is also co-enabled by world-class know-how and knowledge, both in the companies and in Dutch Universities and RTOs, like ARCNL (Advanced Research Center for Nanolithography), VSL and TNO.
- The vibrant Dutch ecosystem of established industrial companies, academia and RTOs, and investment and incubator vehicles, also supports start-ups and ventures addressing the semiconductor equipment market.

This thriving ecosystem forms the basis for innovation and development of leverage points in emerging technologies. Securing an even stronger position for the future. As a result of this strong global position of Dutch companies, the Dutch ecosystem for Semiconductor Manufacturing Equipment Industry has an important contribution to the European sovereignty and to the earning power of the Netherlands.

2. Applications and technologies

2.1. State of the art review

2.1.1. Industry

Continuous innovation over the past 5 decades, has enabled major innovations in the industries using/applying ever improving electronic component and systems, co-enabled by important Dutch inventions. This is underpinned by:

- ASML’s introduction of Extreme Ultra Violet Lithography for leading edge logic and memory technology for sub 5nm IC-nodes and its extension to high NA EUV.
- ASM’s realization of several high-productivity systems to deposit enabling new materials by (Plasma-Enhanced) Atomic Layer Deposition, epitaxy and chemical vapor deposition.
- Besi’s creation of Advanced Packaging Equipment for Exposed Die Molding Wafer Level Packaging (WLP) and Saw singulation stepcut processing.
- Thermo Fisher Scientific’s Transmission Electron Microscopy to measure and qualify materials and transistor structures down to the sub-atomic scale. In addition, the consortium Thermo Fisher, Technolution, TU Delft and Delmic (consortium lead) have developed a multi-beam electron microscope for nanometer-resolution biological tissue imaging.
- Nearfield Instruments’ high-throughput atomic force microscopy enabling non-destructive, in-line, atom-scale 3D on-surface and subsurface metrology.
- Salland Engineering’s specific MEMS test IP, developed together with Saxion, Maser, University of Twente, made it possible to test this kind of semiconductors without the physical stimulation.
- Deployment of expertise in other area’s such as in the “Einstein Telescope”, knowledge on contamination control for EUVL is applied in space instrumentation, and systems engineering and nanofabrication expertise is now applied to quantum technologies.

Wafer-Fab equipment

The *forefront* of Wafer-Fab Semiconductor Manufacturing Equipment is currently applied to *Logic* and *High-Performance Memory* which is used mainly in portable devices as well as advanced cloud computing (incl. AI) and data storage platforms. Currently, double, triple and quadruple patterning are used with immersion (DUV) lithography in combination with advanced materials deposition (led by ASML and ASM respectively), single patterning EUV lithography (ASML as single supplier) is used to realize line widths of less than ~ 14 nm for IC nodes of 5nm and lower, and 3D NAND Memory with 128 layers and more. Creating a leading-edge IC nowadays is a process consisting of several hundreds of individual steps.

A state-of-the-art IC-Fab typically applies EUV for the critical patterning layers, and iDUV (immersion Deep UV) for the less critical layers, with a mix-and-match of EUV and iDUV equipment to secure correct relative placement (Overlay) of each layer with an accuracy of 2.5 nm.

High resolution, accurate, reliable and automated analysis of the results of lithography and deposition steps is required, with TEM solutions provided by Thermo Fisher Scientific being a critical technique used by in fabs, often with multiple systems, during R&D of the processes and production ramp-up to ensure the correct selection of process parameter windows and high yield operation of the wafer fab.

From 2024 onwards, enabled by current Deposition, Lithography, Etch, Processing, Analytical and Metrology tools – a significant part of it provided by Dutch vendors - and their performance, the 2nm technology node is to be ramped-up by market leaders Intel, TSMC and Samsung, and solutions for 1.4nm and beyond are being explored.

Major trends in the wafer-fab equipment industry are:

- Continuous scaling of dimensions, illustrated by imec’s device development roadmap, depicting progress from the N2 (2nm) node in 2024 to the A7 (7 Angstrom) node in 2030, continuing Moore’s law, see Figure 2.
- Dimensional scaling will still progress, albeit, not with the 0.7x per node the industry has been used to. The metal pitch is expected to shrink from 21nm in 2024 to 16-14nm by 2030.
- Further functional scaling will be achieved by device and material innovation enabling the industry to migrate towards 3D transistor & memory devices, such as moving from the present FinFET to Gate All Around and 3D CFET devices.
- Lastly there will be a trend to introduce scaling boosters like back side power distribution, Super Vias and Through Silicon Vias (TSVs) to enable stacked die/wafer solutions.
- In the power semiconductor market, wide band-gap materials such as SiC, GaN will have to be further developed and new device architectures with materials such as high-k dielectrics, and other wide band-gap materials such as AlN and GaO will be developed.

Figure 2: Potential roadmap extension of high-performance CMOS logic, imec

For new technology nodes, new materials are required, *either* to optimize electrical properties, in which case the materials stay in the structure, *or* to enable the creation of challenging 3-dimensional geometries, in which case the materials might sometimes be sacrificial. Deposition of materials has to be more and more selective in the areas to deposit on, the layer thickness, the deposition on horizontal and/or vertical surfaces. Equipment with such capabilities includes the ALD tools by ASM, which are more selective than (Chemical Vapor Deposition (CVD) and other processing tools. The increasingly strict low-thermal, low-voltage, and low-leakage budget requirements for state-of-the-art process flows increase these challenges considerably.

Productivity improvement and energy reduction remain a constant drive in the industry. To reduce cost, the number of wafers that are processed per hour is constantly pushed upwards by Wafer-Fabs at an equal or lower power consumption. This can be achieved by *either* throughput improvements of semiconductor manufacturing equipment and workflow *or* process simplifications. (Although throughput differs strongly per manufacturing equipment segment, like in lithography throughput levels in DUV currently are around 295 wafers per hour and 170 in EUV, whereas, throughput in deposition might take up to a few minutes of single wafer deposition processes, with mini-batch taking up to ten minutes per wafer, and for full batch up to a few hours in a vertical furnace, depending upon the chemical process and desired film thickness.) For all equipment this means a push for higher throughput and higher yield, as well as better process control to limit additional process steps or rejected wafers. More advanced equipment both in patterning, processing and metrology is the result. The kWh/wafer is a key KPI to drive innovations for sustainability.

Another trend is the need for more efficient methods for equipment design and realization to mitigate the growing technical complexity and increased labor demand. The ever-increasing technical complexity necessitates significant increase in labor to enable the design and realization of future semiconductor manufacturing equipment solutions, be it in lithography, etch, deposition, metrology or analytical characterization. Without efficiency improvements, the local labor marked would not be able to supply enough highly skilled personnel resulting in slower innovation than technically possible. Eventually this will have an impact on profit margins, as the increase in technical complexity is slowly outpacing the achieved throughput improvements.

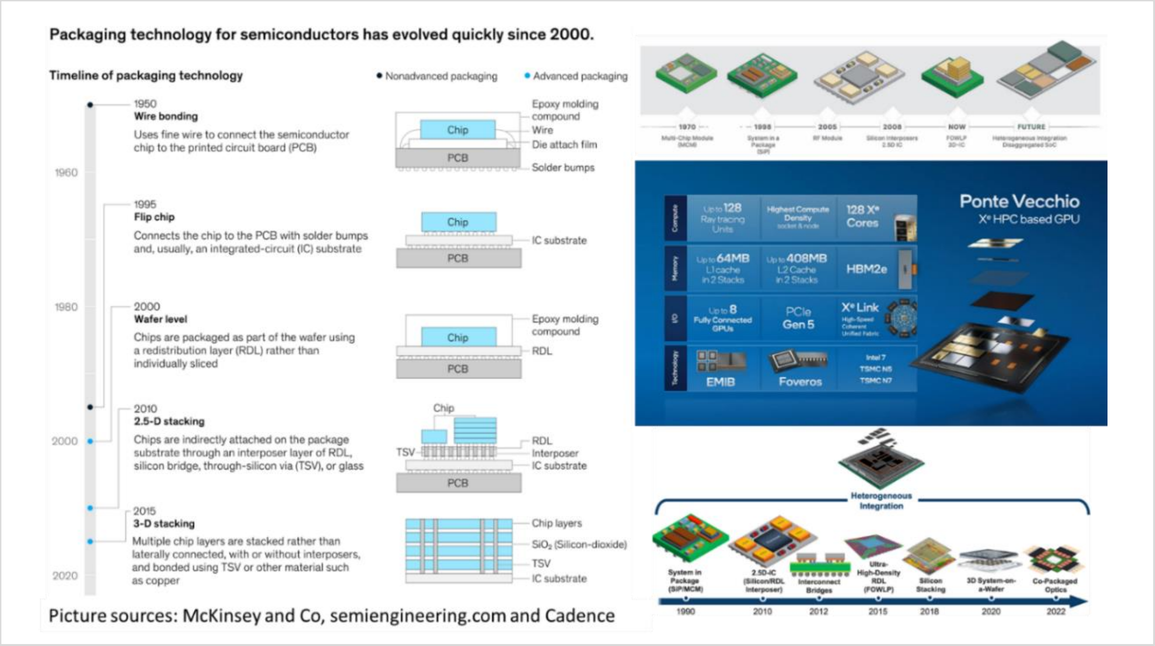
In the area of manufacture there is the trend of further automation, e.g., Industry 4.0 and 5.0, needing more exchange of data, requiring secure access to design data into manufacture and manufacturing information from equipment in the production environment. This links to the Smart Industry roadmap.

Lastly there are the environmental aspects, where there is the elimination of harmful & polluting materials, like to phase out PFAS containing materials in equipment and processes and High Voltage insulating gas, SF6, on one hand, and to reduce energy and material consumption on the other. Most of the stock-listed equipment companies' operations in NL, have committed themselves to ambitious NetZero strategies. To achieve these, they drive to make equipment more efficient on energy, water and material consumption, and address recycling opportunities for components utilities such as gases (notably hydrogen and carbon dioxide) and processed materials. Most often, such efforts involve close collaboration with equipment component and material suppliers. Refurbishment and re-use of components, sub-systems and systems is also a long-term activity gaining momentum.

All-in-all, this represents a major challenge to the international semiconductor industry in the areas of lithography, material innovation, processing, assembly, process control, analysis and testing, as well as an opportunity to the well-positioned Dutch equipment vendors and their network of suppliers.

Assembly equipment

Since 2000 packaging technology of semiconductors has evolved considerably, see Figure 3.



Picture sources: McKinsey and Co, semiengineering.com and Cadence

Figure 3: Evolvement of semiconductor packaging technology since 2000.

The *forefront* trends in Assembly equipment development are:

- To maximize the benefits from ICs made for IC-nodes of 7 nm and less, going *from* simple wire bond *to* Ball Grid Array/Flip Chip, *to* (Fan-Out) Wafer Level Packaging without substrate interposer, to complex 3D structures with Through Silicon Vertical Interconnect Accesses (“TSVIA”), micro-bumps and thin dies, and *to* wafer-to-wafer bonding to speed up production of 3D ICs.
- Functional diversification of technologies, where digital electronics meet the analog world, using advanced assembly/packaging of heterogeneous pieces of chips (“chiplets”) and of chips, sensors and/or smart antenna components. (Obviously, these trends are closely related to the trends formulated for (front-end) wafer-fab equipment, amongst others creation of silicon vias and backside power distribution networks).
- An ongoing focus on enhancing functionalities of heterogenous systems by combining “traditional” semiconductors with integrated photonics components or chiplets. Trend that is also being largely spurred on by large investments from for instance “National Growth Fund projects” (Quantum Delta NL, PhotonDelta and NXTGEN Hightech) and other (public private) projects and partnerships.
- Addressing high speed component transfer by the assembly industry, with ambitious goals of developing transfer capability up to 1 million components per hour (without contact) by 2028.

Besides this technological frontier, trends for Assembly equipment are:

- Factory automation to increase product reliability with multi-facetted device inspections, sorting and advanced tracking and tracing as well as data storage through full production lines.
- Product developments for highly specialized applications such as medical applications, organ on chip devices.
- Application for laser satellite communication and agrifood.
- Power modules/discrete devices for electric cars, power grids and industrial equipment and Integration of optical inputs/outputs in electronic IC's.
- Development and application of 3D printing technology in heterogeneous integration, covering materials, process and equipment.

Test Equipment

The forefront development of Test Equipment is taking place in Japan and the USA. In the Netherlands there are a few companies contributing to this Test Equipment market, like:

- NTS Optel as SME in automated Optical Test Equipment in the application areas of Cell Phone, VR, AR and MR. Common products in these applications are DOE and MLA.
- BE Precision Technology that designs and manufactures probe-cards which are crucial parts of a wafer test set-up, and which are the mechanical interface between a test system and the bond-pads on the wafer under test.
- IMS that develops new metrology and test equipment for integrated photonic chips. The first machines are due to reach the market by 2024.
- Salland Engineering that designs and manufactures high performance or high channel density instruments for automatic test equipment (ATE), including automation software and data analysis, as well as custom test solutions throughout the production cycle of Silicon-Based Devices.[7]
- ITEC develops automated test equipment solutions for discrete analog small signal and power semiconductors (wafer test and final test) and automated optical inspection (lead frame, post clip bond, 3D inspection).

Opportunities for new business development and related R&D in test equipment:

- Need for cost-effective test solutions production for 3D ICs using advanced packaging (e.g., using chiplets).
- Need for test solutions for special ICs, like IC-packages with integrated photonics or "lab-on-a-chip".
- Need for better and faster analysis tooling to do faster product characterization.

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[7] Several Dutch companies offer test services to the Semiconductor Manufacturing Industry (like Maser Engineering) without manufacturing and sales of test equipment.

2.1.2. Science & RTOs

In *Table 2,* an overview is given of parties and the knowledge & technology domain they are active in.

Name	ASM	ASML	Besi	Demcon	Eurofins	ITEC	itility	IMS	KMWE	MI-partners	Nearfield	Nedinsco	Neways	NTS Group	Prodrive	Reden	Salland	Saxion	SolMates	SoS	Technolution	Tempress	ThermoFisher	Trymax	VDL-ETG	ARCNL	TNO	TUDelft	TU/e	UTwente	VSL
Optics		X		X							X	X		X	X								X		X	X	X	X	X	X	X
Photonics		X													X			X													X
Metrology		X		X		X	X	X		X	X			X			X	X			X		X		X	X	X	X	X	X	X
Thin films	X	X		X	X						X				X				X	X		X	X	X		X	X	X	X	X	X
Material Science	X	X			X						X				X				X			X	X	X	X	X	X	X	X	X	X
System engineering	X	X	X	X		X		X		X	X	X		X	X		X		X	X	X	X	X	X	X		X	X	X	X	X
Mechatronics	X	X	X	X		X		X	X	X	X	X		X	X			X	X	X		X	X	X	X		X	X	X	X	X
Deposition technology	X	X		X															X	X		X	X	X		X	X	X	X	X	
AI & Machine learning	X	X		X		X	X				X				X		X		X		X		X	X	X	X	X	X	X	X	X
Software & Control	X	X	X	X		X	X			X	X	X	X	X	X		X		X	X	X	X	X	X	X				X	X	X
Cleaning	X	X			X				X	X	X		X	X	X		X					X	X	X	X		X	X	X		X
Design Automation	X	X				X	X						X	X	X							X	X	X	X			X	X		
Design for Sustainability	X	X	X				X					X	X		X								X				X	X	X		
Production technology	X	X	X		X	X	X		X			X	X		X		X	X					X		X		X	X		X	
Model based System engineering		X					X								X	X							X		X		X		X	X	X

Table 2: Division of Knowledge & Technology domains across parties

Knowledge and Technologies for Wafer-Fab Equipment

For Lithography equipment, beyond-state-of-the art knowledge and technology is generated by many thousands of R&D specialists at ASML and its *industrial/private* partners and suppliers.

In the case of Analytical and Metrology Equipment, beyond-state-of-the art knowledge and technology is generated by hundreds of Thermo Fisher Scientific R&D specialists and its ecosystem for, e.g., new electron microscopes solutions (using e.g., TEM/STEM/EELS/EDX [8], automated workflows and metrology, AI, etc.) for fast, sub nanometric 3D imaging and chemical analysis, and other measurement equipment to enable the development and near line process ramp and production monitoring for leading IC nodes.

Nearfield Instruments, with around 100 R&D&E engineers, together with development partners in the high-tech ecosystem, continuously generate new technologies and know-how to realize non-destructive, high-throughput on- and subsurface atom-scale metrology.

In ASM, which has a globally decentralized network, many new materials and deposition technologies are being developed, connecting the Netherlands to a vast materials innovation network.

In addition to this private/industrial R&D:

- ARCNL develops, in a PPP (Public Private Partnership0, beyond state-of-the-art knowledge and technology for Computational Imaging, Contact Dynamics, EUV Generation & Imaging, EUV Photoresists, EUV Plasma Processes, High-Harmonic generation and EUV science, Light-Matter Interaction, Materials & Surface Science for EUV Lithography, Nanolayers, Nano-photochemistry, Nanoscale Imaging and Metrology [9].
- TNO develops, in PPP's, business contracts or by spin-off creation, beyond state-of-the-art knowledge and technology for Molecular Contamination Control and enhanced lifetime for EUV optics, particle contamination control for EUV lithography and assembly equipment, optical column conditioning for immersion and dry DUV lithography systems, opto-mechatronics for new lithography concepts, new metrology solutions for beyond 7nm nodes and for heterogeneous integration based on combined optics, acoustic, scanning probe, and quantum technologies, Thermal & Flow plus vacuum & plasma solutions for iDUV, new sensors and actuators for enhanced machine control, unique equipment for research, and material and concept qualification, alternatives for PFAS and other harmful materials, new methods for optical design, AI based digital twinning techniques for equipment R&D and assembly, AI for preventive maintenance, architectures for embedded software.

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[8] (S)TEM = (Scanning) Transmission Electron Microscope, EELS = Electron Energy Loss Spectroscopy, EDX = Energy Dispersive X-ray

[9] https://arcnl.nl/research

- Universities and other institutes such as Eindhoven University of Technology (TU/e), University of Twente (UTwente), Delft University of Technology (TU Delft), VSL (National Metrology Institute) and DIFFER, develop with involvement of private/industrial companies beyond-state-of-the-art knowledge and technology as well as provide new talent on various topics, like:
    - Mechatronic and related power electronics solutions for wafer stages operating at beyond 30G accelerations in combination with (sub) nanometer level accuracy and precision.
    - Advanced measurement, control, and optimization techniques (including AI and Machine learning) to operate mechatronic systems at their maximally capable accuracy and throughput.
    - Advanced construction design techniques, (meta-) materials, and manufacturing techniques for extreme-precision and stability of mechanical structures.
    - EUV (deformable) optics, optical surfaces and pellicle technology.
    - Flow and temperature solutions for cooling concepts in near vacuum conditions.
    - Tribology research for e.g., improved understanding of wafer deformations during movements.
    - New mechanisms and technologies for clean substrate transfer.
    - Models for prediction of particle generation and transport to achieve high levels of cleanliness.
    - Plasma technologies to manage nano contamination in equipment.
    - New metrology and sensor concepts, including realization of test and qualification equipment.
    - Advanced materials, plasma physics and chemistry related to contamination control and behavior of systems in extreme conditions.
    - Machine learning and digital twinning for predictive maintenance to achieve increased availability of equipment.
    - Artificial intelligence, machine learning and other computing methodologies to handle the large big-data volumes produced in Holistic/Computational lithography and metrology.
    - Design automation to optimize equipment performance, lower cost, reduce over-dimensioning, improve labor productivity, and improve resilience through platforms and standards.
    - New materials and deposition technologies for future devices, both in More-Moore and More-than-Moore areas.
    - Model Based System Engineering, MBSE.
    - Knowledge of Design for Sustainability.

Knowledge and Technologies for Assembly Equipment

For the advanced Packaging Equipment, beyond-state-of-the art, knowledge and technology is generated by a few hundred R&D specialists at Besi and its *private/industrial* partners and suppliers to meet the technical challenges as described in Section 2.1.1.2 ("Assembly equipment"). Besi is the market leader in nano-scale wafer level assembly using high precision die to wafer assembly, and Besi is investigating advancements in the precision and productivity to enable 3D IC integration roadmaps. This could give synergy with ASML and European Foundries for specialty ICs. As of today, PPP projects are done only in European projects that also include universities and RTOs in the Netherlands. But PPP projects are also done by the National Growth Fund (like NXTGEN Hightech, PhotonDelta and Quantum Delta). In these projects companies intensively work together to develop relevant cutting-edge solutions that make semicon assembly equipment tools faster and more accurate. But also the lack of specialized tools for integrated photonic chips is being addressed in these PPP's.

Companies in the Dutch ecosystem are also dedicated to continuously develop and expand on their technological knowhow. Companies like Nexperia/ITEC, K&S, Sempro, Besi, Etteplan, IMS, etc. are continuously developing their OEM offerings and are increasing speed, precision and sustainability of their machines, in order to make semiconductor assembly more efficient and future proof.

Advanced packaging knowledge and technology is also developed at the Chip Integration Technology Center (CITC) in Nijmegen which explicitly focused on: packaging of chiplets (system in package), advanced photonic packaging, power electronics, design and material characterization for RF devices and additive packaging manufacturing.

Beyond state-of-the-art knowledge and technology also needs to be developed for assembly equipment for new package formats that support the energy transition. Examples are die attach equipment for Ag- and Cu-sintering and high-volume compound power modules with single or double exposed area’s to increase power density.

Knowledge and Technologies for Test Equipment

Several private companies in the Netherlands develop knowledge and technology in the field of test equipment (see page 11, section Test Equipment). In addition, beyond state-of-the-art knowledge and technology is being developed at universities, for instance at TU Delft on testability of emerging computing paradigms using novel devices, which may become important for novel Test Equipment[10]. Saxion, as a University of Applied Science, works with industry on optimalisation of new wafer-test processes and data handling for more-than-Moore devices such as MEMS and photonics. In addition, the PITC (Eindhoven and Enschede) and CITC (Nijmegen) are codeveloping new integrated photonic test knowledge and technologies in collaboration with several industrial partners, to bring these new techniques to market.

2.2. Developments in present and future markets and societal transitions

The market pull in the past years came primarily from high demands for conventional consumer devices (in particular Smartphones), related communication network devices (4G, 5G) and data centers (and associated high data rate and switching capacity optical communications technologies requiring semiconductor devices). In addition, there are the societal challenges associated with the 3 transitions in Energy & climate, Digitalization and Circular Economy which are expected to result in *additional* fast-growing markets for Electronic Components and Systems.

Digitalization

For example, the 5G IoT market in 2021 is $2.6B and is expected to grow to $40B in 2026. A CAGR of 73%. Or the healthcare Micro-technology market with 11.6B in 2020 which is expected to grow to $21.3B in 2025, a CAGR of 11%, driven by an increased use of remote diagnostics health care (lab-on-a-chip) and connectivity to cope with an aging population. This requires lowering the device production costs either through increased test throughput or more complex (e.g., parallel) test methods. Eliminating production waste via better process monitoring can also improve circularity in

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[10] https://www.tudelft.nl/ewi/over-de-faculteit/afdelingen/quantum-computer-engineering/computer-engineering/staff/said-hamdioui/

the production chain. Both goals can be achieved by innovations in test technology for the R&D, wafer or final test phases of the production cycle.

In general, there is mutuality across solutions like the use of AI in our systems and usage of Semiconductors as the enabler of digitalization.

Energy & Climate

Semiconductors are enabling electrification, with a $1.4B market in 2020 which is expected to grow to $4.5B in 2026, a CAGR of 25.9%.

According to external studies, 1 kWh spent in production in a new manufacturing line helps conserve 4 kWh of energy globally. In addition, smaller and novel transistor and memory structures consume less energy while boosting computing performance. However, this does not mean that semiconductor manufacturing equipment makers are “off the hook”. The industry itself grows and its consumption is expected to go up by 4x by 2040, hence there is a lot of pressure for the industry to limit energy usage, for which further innovations are required. Next to that, new technologies may be required to manufacture parts (in the supply chain) in a more sustainable way, possibly using new/alternative materials.

The promise of energy-efficient computing for data-intensive applications like artificial intelligence, cloud computing, and autonomous electric vehicles increasingly relies upon advances in material research and the ability to construct 3D nanostructures. To make this possible extensive novel materials research and equipment development is required.

In order to enhance energy efficiency of invertors used in renewable energy and electric mobility wide bandgap semiconductors like SiC, GaN and some lower TRL level wide bandgap materials are essential. The enhanced efficiencies will result in lower levelized cost of energy and extend the range of electric mobility solutions to allow further adaptation. Also, assembly will play an important role.

Circular Economy

Equipment for a lifetime, through refurbishment & re-use of parts and upgradability. For example, 95%, of ASML machines ever built are still in use. ASML and Thermo Fisher Scientific have re-use programs in place aiming at maximizing re-use (= repair/remanufacture) of returned parts to create new modules or parts.

In the recent past, ASM refurbished all of the available legacy vertical furnace systems. For its novel SiC epitaxy systems, a constant component refurbishment flow drives up-time of the system, while reducing waste.

Another example would be deployment of ultra-low-cost ID tags (Solutions on Silicon) to packaging in order to enable tracking and better recycling.

At ASML there is a packaging program that optimizes packaging for footprint and waste reduction.

2.3. Questions and milestones for this roadmap in 2030

2.3.1. Main Questions

1. How to benefit from Public-Private Partnerships (with co-funding of the Netherlands Enterprise Agency RVO[11]) and support of Applied Technology Projects at universities/RTOs (with funding of the Dutch Research Council NWO[12]) to keep on pushing the limits of key enabling technologies, resulting in semiconductor manufacturing equipment with a good business case for manufacturers of electronic component and systems, in order to respond to the large market pull for innovation?
2. How to ensure that promising ideas, that benefit from public R&D in the Netherlands, are *not* routinely manufactured in the Far East (at lower cost due to state-aid and/or lower taxes), by simple by-passing the Make Industry in the Netherlands and the EU[13]?
3. How to boost involvement of SMEs/start-ups in PPS/TKI-allowance projects in the Netherlands:
    - Make it less expensive to outsource R&D to universities/RTOs?
    - Somewhat less academic research with long-term objective/deliverables, and more industrial research with long-term objectives but *also* with short-term deliverables?
    - RVO/NWO to address the disproportionally large legal overhead to get PPP projects started, e.g. by introduction of standardized templates for IP agreements?
4. How to approach the need for an Industrial policy, for choices, partnerships, strategic alliances?
5. How to ensure that roadmap implementation satisfies long term societal needs and adheres to industry strategy?
6. How to cope with the impact of geographical shifts in the industry – “Re-shoring”?
7. Optimize contributions by RTO, talent development and partner innovation.
8. Building and stimulating ECO systems and communication between eco-systems.
9. How to organize the innovation ecosystem to smoothly transition from low to high TRL?
10. How to enhance knowledge sharing and labor productivity through standards and common design methods and tools?
11. How to reduce the environmental impact of the industry (without hampering progress)?
12. How to bridge the period between R&D and ramping real business. There are a lot of R&D programs but not much after this period where scaling of business and pre-investments are made?
13. How can we secure to be not only an ‘’Engineering country’’ but as well being involved in equipment manufacturing and keep as well semiconductor related production, like Assembly and testing in the Netherlands/Europe to create a more autonomous supply chain?

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[11] https://www.rvo.nl/subsidie-en-financieringswijzer/pps-toeslag-onderzoek-en-innovatie

[12] https://www.nwo.nl/onderzoek-en-resultaten/programmas/htsm

[13] https://www.vdlgroep.com/nl/nieuws/opinieverhaal-chinese-bussen-kosten-banen-in-nederland

2.3.2. Main Milestones in 2030

- Milestones to follow imec roadmap for semiconductor technology.
- ASML (2030): Holistic and High NA Lithography enabling IC nodes at 14 Angstrom and beyond with advanced patterning solutions, competitive wafer throughput, overlay performance, uptime and cost.
- ASM (2030): The world's lead player supplier for ALD and Epitaxy Equipment with leading technology to create ultra-thin films of exceptional material quality, uniformity and conformality for small geometries (to below 2nm IC node) for more complex device structures like Gate-All-Around transistors and advanced DRAM. This includes driving the adoption of ALD with the application of Selective ALD, the introduction of new materials like molybdenum as a replacement of CVD Tungsten/PVD Copper, and improving plasma sources for VHAR gap-fill. Epi gains market share in the transition to GAA and 3D DRAM, whereas the SiC Epitaxy adoption results in market leadership. The newly developed SONORA furnace continues the good momentum, and selective inroads are made with technically differentiated nice offerings. Finally, new opportunities in advanced packaging and heterogenous integration in areas of ASM core strengths are pursued. This all while achieving our NetZero ambition on all scopes.[14]
- Besi (2030): Assembly equipment for advanced heterogeneous integration of systems in three dimensional functional packages and seamless integration of the assembly equipment in the automated factory.
- Thermo Fisher Scientific (2030): higher throughput near-line TEM workflow solutions for atomic resolution structural and chemical analysis, metrology and failure analysis for materials and structures, including 3D, used in sub 3nm IC-node CMOS logic, leading edge memory, and More than Moore devices.
- Nearfield Instruments (2030): high-throughput, non-destructive, in-line probe-based metrology & inspection solutions for 2 nm and beyond process control for the entire semiconductor value chain (advanced wafer processing, specialty nodes and advanced packaging).
- Salland Engineering: development of test IP building blocks to address future test challenges and applicable in high volume, validation equipment and System Level test.
- Smaller Dutch Semiconductor Manufacturing Equipment Companies, Contract Development Companies and Contract Manufacturing Companies work towards increased market shares.
- Some of several new (metrology) machine concepts and technologies by TNO, VSL, universities, and PPP consortia have been introduced in the market by Dutch companies.

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[14] ASML Investor Day 2023

3. Priorities and implementation

3.1. Priorities of implementation

Priority of implementation will be derived from the societal challenges associated with the 3 transitions and the National Technology Strategy short list of technologies.

3.1.1. National Technology Strategy

The National Technology Strategy aims to strengthen technological leadership of the Netherlands by prioritizing key enabling technologies that are local core competences in science and industry. Of the “short list of technologies”, a direct link to the semiconductor equipment roadmap can be identified for “Mechatronics and Opto-mechatronics”, “Micro-electronics”, “Imaging Technologies”, “Artificial intelligence and data science”, “Optical systems and Integrated photonics” and “Quantum technologies”. This is either based on impact of this roadmap on innovation and progress in these technology areas, or the dependence of this roadmap on these technology areas and thereby them being an opportunity for technology deployment in products realizing economic impact. These technologies enable the rapid innovation pace of the Dutch Semiconductor Equipment ecosystem. Moreover, the Semiconductor Equipment ecosystem has been, and will be, one of the most important drivers for technological leadership in these technologies.

In regard to the other technologies on the short list; “Biomolecular and cell technologies”, “(Bio) Process technology, including process intensification” and “Energy materials”, there is a connection with Electronic Components and Systems being the common denominator enabling their innovation. Moreover, in these cases, there is a direct connection in electron microscopy, via two-way innovation flow with e.g. life sciences and materials areas.

However, for the Semiconductor manufacturing Equipment roadmap there are more critical technologies that should not be ignored. As is illustrated in Table 2, besides the 6 mentioned above there are another 11 enabling technologies, of which Material Science (or Advanced Materials) and System Engineering are most prominent. With Advanced Material not only being relevant in Semiconductor manufacturing equipment but also forms the basis to solutions in the other technology domains key to the 3 transitions, like in carbon capture (ALD-driven), perovskite solar materials, solid state batteries and electrification of industry & mobility.

3.1.2. Societal transition

Further priority is derived from the societal transitions. The equipment sectors drive innovations for Electronic Components and Systems with more/other functionality and more embedded electronic computing power and thereby enable solutions for almost all sectors involved in energy, digitalization and circular economy.

3.2. Implementation of this roadmap in public-private partnerships and ecosystems

Besides private investments into this roadmap there will also be implementation through Public Private Partnership (PPP) projects. A PPP typically consists of Large Enterprises, Small & Medium Enterprises (SMEs), Research Institutes and Universities. SMEs are involved both as suppliers to the Large Enterprises and as suppliers in the Equipment Markets. The process followed in creating and maintaining this roadmap is described in section 4.2.

The subjects to address to implement the roadmap:
Common to all equipment development is the challenge to cope with the ever-increasing complexity in their design while remaining competitive at cost and at the same time coping with labor shortage.

Wafer-Fab Equipment

- Lithography systems for advanced Systems-in-Chip. in particular (D) UV (Deep Ultra Violet) and EUV (Extreme Ultra Violet) technology, with associated light sources, optics, sensors, electro-mechanics, vacuum technology (for EUV), temperature stabilization, embedded software, multi e-beam inspection technology and advanced computational lithography software.
- Equipment for manufacturing new materials for nano-structuring technologies, such as for substrate, resist, chemical gases, shielding membranes.
- Equipment for manufacturing thin films, via deposition, epitaxy, diffusion, temperature treatments, etching with the associated factory infrastructure.
- Equipment for wafer processing (cutting, etching, polishing, cleaning, epitaxial deposition, thinning and making alignment marks with a laser.
- Equipment for Minimalfab for “More-than-Moore” ICs using 12.5 mm wafers in sealed cassettes without the need for a clean room.[15]
- Equipment for manufacturing of existing and new technologies for diversified ICs, such as ICs with integrated photonics[16], and “lab-on-a-chip” typically using special microelectromechanical systems (MEMS) devices.[17] [18]
- Equipment for analysis, characterization, dimensional metrology and inspection, including sample preparation, at micro scale to sub-atomic scales with scanning probe, electron beam, X-ray, EUV and acoustic methods for determining geometric, thermal, electrical and chemical properties (multidimensional and multidomain).
- Multidimensional analysis and metrology equipment suitable for 3D extensions of devices.
- Photonic Integrated Circuits metrology equipment.
- Sustainable equipment design.

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[15] https://bits-chips.nl/artikel/dutch-semicon-ecosystem-is-introduced-to-minimal-fab/
[16] https://www.tue.nl/en/research/research-areas/integrated-photonics/
[17] https://www.utwente.nl/en/education/master/programmes/electrical-engineering/specialisation/lab-on-a-chip-systems/
[18] https://en.wikipedia.org/wiki/Lab-on-a-chip

Assembly Equipment

- Equipment for heterogeneous integration enabling System-in-Package (as described in Section 2.1.1.2 Assembly equipment).
- Equipment for wafer level packaging of Exposed die Molded UnderFill (MUF).
- Equipment to manufacture three dimensional functional packages in which the package geometry has additional functions/requirements, next to protecting the electronic device.
- Equipment for assembly of integrated photonics and of other emerging new technologies, like arrays of capacitive micromachined ultrasonic transducers.
- Equipment to increase the reliability of processed devices by inspection, sorting and providing detailed process data on the device level (track & trace), as well as machine level (big data).
- Equipment for biomedical production, upscaling device manufacturing.
- Equipment to manufacture future LED-displays, which require ultrafast, accurate and low-cost pick & place solutions. According to market trend forecasts, this spillover market for pick & place equipment will outgrow the semiconductor assembly market by an order of magnitude.

Test Equipment

- Equipment for testing (on wafer- or module level) emerging and more-than-Moore devices such as photonics, MEMS, LoC and quantum in the future
- Equipment for System level test while testing at wafer or package testing is not sufficient anymore to guarantee the end product quality.
- Equipment and tooling to do faster and easier in Silicon production ramp-up, and which is closer related to high volume test equipment to avoid long correlation exercises.
- Automatic test equipment with smart functions that interpret and provide data across the production cycle, from EDA to final packaging.
- See section Test Equipment, page 11.

What the Dutch government can do to support the semiconductor manufacturing equipment industry:

The Dutch government could help the semiconductor manufacturing equipment industry to grow and prosper by guaranteeing certain conditions are met. This concerns certain policy areas:

- Talent and education:
    - The Dutch government should invest in the availability and quality of STEM educated talent. This applies to all levels (primary, secondary, vocational, and higher education) and STEM studies. STEM education should be a part of the curriculum from an earlier age.
    - There should be no limits on the number of students in STEM studies (no numerus fixus).
    - The Dutch government should invest in being an attractive place for talent to come to the Netherlands (e.g., keeping the 30% ruling).
    - The Dutch government should facilitate and invest more in collaboration within the European Union between RTOs, universities, and companies.

- Infrastructure, mobility, housing and grid congestion:
    - The semiconductor manufacturing equipment industry will grow in the coming decade. This growth should be enabled and facilitated by the Dutch government.
    - The Dutch government should invest in infrastructure and mobility to enable the development of the industry, not only for the industry, but also for the people that work in it.
    - The Dutch government should invest in more affordable housing by building more houses. Talent will not come and stay in the Netherlands without proper housing.
    - Companies are not able to grow if grid congestion is not properly addressed. The Dutch government should prioritize helping companies in the semiconductor manufacturing equipment industry.
- Innovation and industrial policy:
    - The Dutch government should identify current and potential strengths within the semiconductor manufacturing equipment industry and invest.
    - SME and start-ups should be supported by reducing wage taxes to enable lower wage costs.
    - Start-ups and scale-ups should be supported by creating an investment climate for growth (also in view of retaining earlier investments).
    - In regard to financing for companies, “red tape” should be reduced.
    - The Dutch government should create centers of excellence for semiconductor equipment focusing on certain areas (such as optics).
- The Dutch government should actively promote the diversity and excellence of semiconductor equipment manufacturing activities in the Netherlands, also abroad during economic missions.

3.3. Collaboration in, and leverage with, European and multi-national policies and programs

The R&D done in the context of the HTSM roadmap for Semiconductor Manufacturing Equipment:

- Leverages the EU Chips-act and associated initiatives for pilot line and competence center development development
- Leverages the PPP-Clusters: Chips JU (KDT), Xecs, ITEA4, EUREKA, Dutch Programs for PPS/TKI and TTW (Applied Technical Research) for HTSM, in which there is cooperation with Dutch companies, RTOs and universities in National and Horizon Europe collaboration projects.
- Leverages the Strategic Research and Innovation Agenda for electronic component and systems with a full chapter devoted to Semiconductor Manufacturing Equipment;[19]
- Will be done in collaboration with Dutch companies, RTOs and universities in the context of the new Horizon Europe Program.

Related relevant Holland High Tech roadmaps[20] are Electronics, High Tech Materials, Photonics, Printing, Smart Industry and Systems Engineering.

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[19] About | ECS SRIA

[20] Technologies (hollandhightech.nl)

4. Partners and process

4.1. Partners in this roadmap from industry, science, departments, regions and cities

- Science and RTOs: ARCNL, TNO (in particular in Delft and Eindhoven), VSL, TU Delft, TU/e, UTwente, DIFFER, CITC, University of Groningen (RUG), KU Leuven, RWTH Aachen, Saxion.
- University research centers: EHCI, HTSC2.0 (working title)
- Public Organizations in the Netherlands: Ministry of Economic Affairs and Climate Policy (EZK), RVO, NWO
- Europe: European Commission (in Horizon Europe, Interreg and Eureka with National Authorities).
- Regions: Brainport Eindhoven, Brabantse Ontwikkelings Maatschappij (BOM), Provincie Noord Holland
- Cities: Amsterdam (ARCNL), Eindhoven.
- Industry / Private Parties in the Netherlands with activities related to this roadmap (like ASM, ASML, ASMPT, Besi, Boschman, Bronkhorst High-Tech, Demcon, Domicro, Eurofins, Frencken, Heinmade, IBS Precision Engineering, ITEC, itility, KMWE, Kulicke & Soffa Liteq, Malvern Panalytical, MI-Partners, Nearfield Instruments, Nedinsco, Nexperia, Omron, Prodrive, Reden, SoS, SIOUX, Solmates, Solutions on Silicon, Technolution, Etteplan, Tempress, Thermo Fisher Scientific, Trymax, VDL-ETG, Salland Engineering and NTS group).
- National R&D Workgroup on mechatronics. The R&D workgroup aims to be the primary consultative body for the Dutch Mechatronics ecosystem that targets continued international competitiveness through active technological support, initiation and execution of collaboration between OEMs, SMEs and knowledge institutes. In this group, experts from industry and academia join 4x per year to discuss necessary roadmap developments in the field of mechatronics and aim to initiate research consortia between industry and academia.

4.2. Process followed in creating and maintaining this roadmap (with role of SME)

On the basis of *new* concepts and ideas with low TRL (1-3), with as objective to increase TRL to 6-7 (so ready for product development).[21] Idea selection will be based on the expected power to offer solutions for the elimination of technical bottlenecks for:

- Continued IC-shrink and resulting improvement of performance (“More Moore”).
- For enlargement of functionality for (shrunk) ICs and IC-packages (“More-than-Moore”).
- Acceleration of manufacturing.
- Sustainability of ECS production and production equipment.

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[21] https://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf

Starting points will be ideas coming from private R&D (Large Enterprises, Small and Medium Enterprises, Startups), Research Institutes (ARCNL, TNO, VSL, DIFFER, …) and (Technical) Universities.

End points are culminating in (European) pilot lines for manufacturing of electronics, to offer excellent opportunities for innovative new equipment to prove its value in industrially relevant conditions (TRL 6-7).

5. Investments

The following graphs illustrate the investments and benefits in the sector in terms of yearly R&D investment, Revenues, patent applications and jobs in the Netherlands. The numbers are based on input from ASM, ASML, Besi, Nearfield, Prodrive and TNO over the past 10 years showing very substantial increase over time underpinning the economic significance of the sector.

Figure 4: Investments and benefits in the sector in terms of yearly R&D investment, Revenues, patent applications and jobs in the Netherlands. The numbers are based on input from ASM, ASML, Besi, Nearfield, Prodrive and TNO over the past 10 years.

The table below shows the expected yearly investment in this roadmap for 2024 - 2027 in Public Private Partnerships (PPP). The top part represents the total investment based on Industry, RTO, Universities and co-financing of EU and the Dutch ministry of Economic Affairs and Climate Policy (EZK) in EU programs, the Dutch National Growth Fund (Nationaal Groeifonds) and IPCEI. The Industry, RTO and University numbers exclude the EU and EZK co-financing.

Roadmap	**Expectation 2024 - 2027 in Meuro/year**
Industry	**91**
RTO	**9**
Universities	**9**
Groeifonds	**29**
IPCEI EZK co-funding	**18**
EZK co-financing EU + NL projects	**17**
European Commission Co-financing	**9**
Total	**183**

EU programs within roadmap	**Expectation 2024 - 2027 in Meuro/year**
Industry	**28**
RTO	**3**
Universities	**2**
EZK co-financing of EU porgrams	**11**
European Commission Co-financing	**9**
Total	**53**

R&D in NL-only PPPs	**Expectation 2024 - 2027 in Meuro/year**
Industry	**63**
RTO (through TKI/PPS)	**6**
Universities (through TKI/PPS)	**7**
EZK co-financing NL projects	**7**
Groeifonds	**29**
IPCEI (EZK co-funding)	**18**
Total	**130**

Table 3: Overview of R&D investments in public-private partnerships. Numbers are based on running and planned EU (Chips JU and KDT JU) projects, Eureka, TKI/PPS and NGF (Nationaal Groeifonds – National Growth Fund) activities related to this roadmap. Upper table: Investments in all PPPs, incl. co-funding by EZK (Ministerie van Economische Zaken en Klimaat / Ministry of Economic Affairs and Climate Policy) and European commission. Middle table: R&D investments in the PPPs enabled by the Horizon Europe/KDT programs and EZK co-financing.[22] *Lower table: NL-only investments for R&D in public-private partnership covered by Industry, RTO/University through TKI/PPS contribution, NGF, Eureka and IPCEI.*[23]

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[22] The values were estimated by using the combined European PPP ecosystems of ASML and Thermo Fisher Scientific, and by using the investment data of Besi, ASM, Nearfields, Solmates, VDL-ETG, VSL and ITEC

[23] The lower table includes investment data from the parties who have shared these data (~ 20% of those asked).

The middle table shows the part of the expected PPP investments in this roadmap based on EU programs which cover KDT JU and planned Chips JU projects. In here, the co-financing numbers of the EU and EZK reported.

The bottom table shows the NL-only PPP investments in which is through Eureka and TKI/PPS and the National Growth Fund.

Overall, the total private R&D investments into this roadmap, (see Figure 4), with close to 3.5B Euro in 2022, well exceeds PPP investments of 183M/year. Which on one hand shows the relevance to the industry but on the other that PPP investments are rather modest, specifically in relation to an approx 23B/year industry (export) for the Netherlands.

Looking ahead to 2024-2027, due to the change toward societal mission oriented public funding in the EU and the Netherlands, the estimated investments in this roadmap are conditional to continuation of sufficient public support to PPPs for Semiconductor Manufacturing Equipment.

6. Conclusions

Semiconductor manufacturing equipment is of key economic and strategic importance to the Netherlands.

In all domains of this roadmap the sector is faced with an incredible pace of innovations. In Wafer fab equipment this is driven by increased complexity and interdependencies of technologies that require mastering at every next node. In assembly equipment there is the drive for integration at package level, pushed by demand for more system functionality, enabling heterogeneous integration at chip level to the extent that assembly technology may find its way in front-end chip manufacture. And in test equipment innovation is pushed by both the need to keep pace with performance improvement realized in More Moore, as well as to find process control solutions for 3D monolithic devices and heterogeneous integration.

These developments make the Dutch semiconductor manufacturing equipment industry thrive: the Netherlands is internationally recognized to excel in complexity and high paced innovation. However, we cannot afford to get too comfortable. The (public) boundary conditions are not keeping pace with the needs of the successful and growing sector: talent is in short supply, the infrastructure at TO2 institutes is out of balance with similar resources in other European countries and the volume of this sector, the upscaling capital for scale-ups is falling short to keep and build position for equipment in renewing and new innovative supply chains.

Moreover, the financial overview demonstrates a volume of about 144 mln/year for Dutch Public Private Partnerships. We consider this as too modest for a ~23 Bln/year industry (export) for the Netherlands. It is unlikely that this incredible ROI can be maintained at the long run, especially in view of all the government involvements in other countries.

In order to keep ahead and stay competitive the industry needs increased effort in:

- Talent development: capacity, education and retainment of talent. For this sector this means efforts in STEM subject in general and specifically in mechatronics, opto-mechatronics, optical design and systems engineering.
- Infrastructure: keeping pace with investments in other (EU) countries. The Netherlands should position itself as the equipment supplier of Europe and the world, including the infrastructure and access. For talent development, lab development, education environments are needed.
- Nurture/support of new businesses, especially in the scale-up phase.

With the recent geopolitical changes and the renewed ambition of reshoring some of the chip production in Europe, it is crucial to keep supporting and stimulating local equipment production as well. Major efforts need to be put on the continuous stimulation of the R&D and production of this equipment in the Netherlands. This all can be done with ongoing availability of PPP’s. Companies depend on these partnerships in order to be able to develop products and technologies that span further than their direct roadmap allows them to do.

These partnerships also allow the companies to further expand their collaborations with knowledge institutions and RTO’s. Together they play a crucial role in maintaining existing positions and to expanding in emerging technologies and capabilities. It is only with continuous support of the semiconductor equipment manufacturers and developers that we can tackle the societal and strategic challenges as defined in this document.

The EU Chips Act mobilizes large investments from both private and public sources. Public national funding and strategy is required, however, to make part of these budgets work for the Netherlands. Without that, most of the funding and resources will flow to other regions within the EU, which would be detrimental to the position of the Dutch ecosystem.

Chip manufacturing is the focal point of the EU Chips Act. However, for no other EU member state is the role of manufacturing *equipment* so important as for the Netherlands. We ask the Dutch policy makers and government to lobby for the importance of *equipment*, next to chips, within the EU Chips Act.

At Dutch TO2 (TNO) institutes the unique R&D&I facilities can be made available to SME only via commercial exploitation models, in contrast to facilities at RTOs in other member states which are state funded. In this way Dutch SME receives far less support than SME elsewhere.