HTSM roadmap for Semiconductor Manufacturing Equipment

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Contents

1. Societal challenges and economic relevance

1.1 Societal challenges addressed in this roadmap

This roadmap finds its origin in the *challenging demands* coming from *society* for Electronic Components and Systems ("ECS") with more/other functionality and more embedded electronic computing power to enable:

- Electronic devices for consumers, like calculators, desktop PCs, Mobile Phones, Laptop/Notebook PCs, LED lamps, Flat Panel Displays, Digital Radio/TV, PDAs, Digital Cameras, Game Consoles, Smartphones, Tablets, Internet-of-Things devices, Driver-Assist/Hybrid/Electric Cars, and Rooftop Solar Energy Systems;
- Electronic devices for professional applications, like medical devices, industrial devices and communication & computation devices such as for massive data centres with High Performance Computers for Cloud Computing;
- Wired (cables, optical fibers) and wireless networks (WiFi, 3G→4G→5G→…);
- Solutions for societal challenges in domains, like "Energy transition and Sustainability", "Agriculture, Water and Food", "Health and Care" and "Security".

Because of this continuous demand for more, faster, smaller, less power consumption and more diversification, there is continuous pressure to continue Moore's law by pushing limits of *available* technology to the next level of performance and by developing *new* technology when existing technology does not bring the benefits required by the next generation devices and applications.

Over the past 5 decades, this has evolved into a thriving digital value chain, in which Semiconductor Manufacturing Equipment forms the base by enabling the manufacturing of the required ECS, i.p. of: IC-modules for very high-density interconnect with silicon interposer ("chiplets"), ICs, Packages of ICs, and of Boards with ICs.

Progress in computing power, sensing, actuation, connectivity and data storage drives innovation through technology advances in many other industries:

- *Using evolving state-of-the-art ECS* (sub-system and system manufacturers);
- *Relying on evolving state-of-the-art* ECS (like software and services industries with underlying Artificial Intelligence, Augmented Reality and Cloud Computing technology development).

This has resulted in many high-value jobs. It has become a major societal challenge to defend and extend this. The Semiconductor Manufacturing Equipment Industry in the Netherlands is determined to continue innovations to beyond state-of-the-art well into the coming decade in order to meet societal demands and challenges that require advanced ECS-based systems and ECS-enabled software & services.

1.2 Connection with thematic Knowledge and Innovation Agenda's[1]

Semiconductor Manufacturing Equipment also enables many solutions pursued in the "Knowledge and Innovation Agendas" ("KIAs") that address, through ECS, additional societal challenges specified by the Dutch government. This will be explained in Section 2.2 ("Developments in present and future markets and societal themes"), in Section 3.1 ("Priorities of implementation"), and in the Appendix.

[1] https://www.topsectoren.nl/innovatie

1.3 World-wide market for this roadmap, now and in 2024

1.3.1 Market for Semiconductor Manufacturing Equipment

According to VLSI Research (4/2020) the world market for Semiconductor Manufacturing Equipment is as indicated in Figure 1. This figure shows that the maximum addressable market for Wafer-Fab equipment in 2019 is by far the largest segment of the total market (in NL addressed by e.g. ASML, ASMI and Thermo-Fisher with their ecosystems), followed by Test Equipment that is a factor 10 smaller (without major Dutch players listed in the market overview of VLSI Research), and by Assembly Equipment (factor 17 smaller, in NL addressed by e.g. BESI).

<table>
<tr><th colspan="3">Semiconductor Manufacturing Equipment
2019: $61,7B
2024: $80,1B</th></tr>
<tr><td>Wafer-Fab Equipment
2019: $53,2B (86.2%)
2024: $69,6B</td><td>Assembly Equipment
2019: $3.0B (4.9%)
2024: $4,0B</td><td>Test Equipment
2019: $5,5B (8.9%)
2024: $7,2B</td></tr>
</table>

Figure 1: World Markets for Semiconductor Manufacturing Equipment [2,3]

The size of the addressable markets and the market shares of Dutch companies, directly reflect the amount of R&D and R&D-investments by Dutch companies addressing those markets, which in turn determines the amount of in-cash/in-kind support of these companies for R&D by Universities and RTOs eligible for "PPS/TKI-allowance".[4]

1.3.1.1 Wafer-Fab Equipment

According to VLSI Research (4/2020), the world market for Wafer Fab Equipment consists of Cleaning & Etching Tools (28%) , Deposition & Related Tools (25%), Lithographic & Mask Making Equipment (27%), Process Diagnostic Equipment (12%; including metrology), Chemical Mechanical Polishing Equipment, Ion Implanters, Other Equipment.

<u>Examples related to the Netherlands:</u>

- ASML (with head office in Veldhoven) and its ecosystem of partners and suppliers address the Lithographic Equipment with built-in Measurement/Diagnostic Equipment for Holistic Lithography. Into the total Wafer-Fab Equipment market of $53,2B in 2019, ASML sold €11.8 billion (~$13,1 billion, so ~ **25%** of the addressable world market, with 100% for EUV Lithographic Scanners).[5]
- ASMI (with head office in Almere) sold into the total Wafer-Fab Equipment €1.284 billion (~$1.4billion, so ~ **2.6%** addressable world market share).[6] ASMI's Atomic Layer Deposition ("ALD") Product lines enjoyed strong double-digit growth in 2019, with ALD continuing to represent more than half of the ASMI equipment revenue. ASMI's other product lines also contributed strongly, led by the Epitaxy product line.
- ThermoFisher Scientific (head office in USA) has its main R&D and manufacturing site for high-end Transmission Electron Microscopes ("TEM") in Eindhoven. High-end TEM includes product lines for the semiconductor market, in which ThermoFisher is the market leader. According to VLSI Research, ThermoFisher (with a total revenue of $5.5Billion of the Analytical Instruments Group

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[2] https://view.publitas.com/cfreport/besi-annual-report-2019/page/1, see Annual Report 2019 and VLSI Research-April2020 for Wafer-Fab Equipment.
[3] VLSI Research, 4/2020; 2024 values: calculated using same growth as predicted for Wafer Fab Equipment
[4] https://www.rvo.nl/subsidie-en-financieringswijzer/pps-toeslag-onderzoek-en-innovatie
[5] https://www.asml.com/en/investors/annual-report/2019
[6] https://www.asm.com/Downloads/2019_ASMI_Annual_Report.pdf

to which ThermoFisher Eindhoven belongs) sold $199million (so ~ **3.8 ‰** of the addressable world-market share) into the Wafer-Fab Equipment market.
- The Dutch Semiconductor Manufacturing Equipment suppliers form vibrant ecosystems together with OEM module suppliers like VDL-ETG, Demcon, Prodrive, Sioux and others. These OEM module suppliers also supply to other international Semiconductor Manufacturing Equipment companies.

1.3.1.2 Assembly Equipment

According to VLSI Research (7/2019), the world market for Assembly Equipment amounted in 2019 to $3,0B and consists of Equipment for Wire Bonding (~ 23%), Die Attach (~30%), Packaging (~18), Plating (1%) and Other (Inspection, Dicing; ~28%).[7]

<u>Examples related to the Netherlands:</u>

- BESI (with head office in Duiven) sold €356 million (~$395 million, so ~ **13%**), with most revenue (~80%) generated with Die Attach Equipment (82%), followed by Packaging Equipment (15%) and Plating Equipment (3%).[8]
- Other companies, like Boschman, K&S (with Head Quarters in Singapore with part of its R&D in the Netherlands), and Solmates.

1.3.1.3 Test Equipment

According to VLSI Research (6/2019), the world market for Test Equipment was in 2019 $5.5B and consists of T&M systems to optimize production of ICs for Memory, Logic, System-on-Chip, Micro Processors, Graphics Processors; Wireless Communications, etc.

<u>Example related to the Netherlands:</u>

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.

1.3.2 Markets enabled by Semiconductor Manufacturing Equipment

The Semiconductor Manufacturing Equipment Industry enables many markets beyond its own market, with a total value that far exceeds the value of its own business (see Figure 2). Hence, continued innovations in this equipment enables continued innovations in many large 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, such as equipment for bio-medical instrumentation, or space & astronomy instrumentation.

[7] The 2019 world market ($3.0B) for Assembly equipment was significantly less than the 2018 world market ($4.5B).
[8] https://www.besi.com/fileadmin/data/Investor_Relations/Investor_Presentations/Investor_Presentation_May_2020.pdf

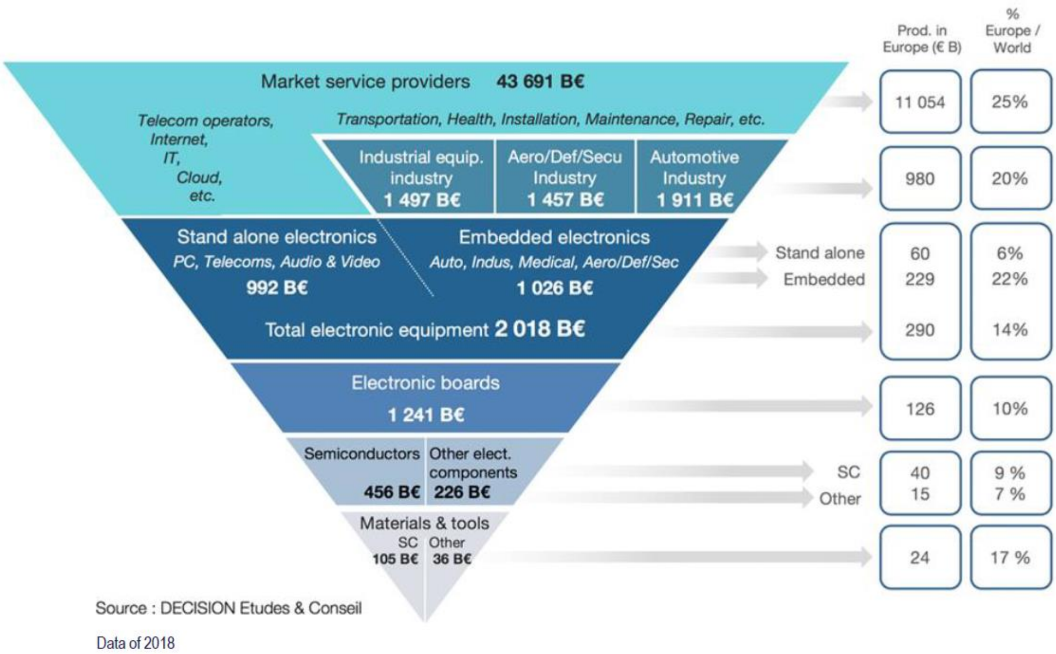

Figure 2. Markets enabled by Semiconductor Manufacturing Equipment.[9]

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

- The Netherlands has a strong global position for Semiconductor Manufacturing Equipment. This has been quantified with examples in Section 1.3.1.
- This strong global position is co-enabled by many Dutch OEM suppliers, like VDL ETG, Demcon 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, TNO).
- 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 ECS, *co-enabled by important Dutch inventions*. Proof can be found in the introduction by:

- ASML of Extreme Ultra Violet Lithography for leading edge logic and memory technology for sub 5nm IC-nodes;
- ASMI of several high-productivity systems to deposit enabling new materials by (Plasma-Enhanced) Atomic Layer Deposition and Epitaxial Depositions;
- BESI of Advanced Packaging Equipment for Exposed Die Molding Wafer Level Packaging (WLP);
- ThermoFisher of Transmission Electron Microscopy to measure and qualify materials and transistor structures down to the atomic scale.

[9] https://efecs.eu/publication/download/presentation-khalil-rouhana.pdf
http://www.decision.eu/wp-content/uploads/2020/02/ECS-study-presentation-of-Key-findings.pdf

2.1.1.1 Wafer-Fab equipment

The *forefront* of Wafer-Fab Semiconductor Manufacturing Equipment is currently lithography for *Logic* and *High-Performance Memory* which is used mainly in portable devices as well as advanced cloud computing and data storage platforms. Currently, double, triple and quadruple patterning is used with immersion (DUV) lithography, and single patterning EUV lithography is used to realize line widths of less than ~ 14 nm for IC nodes of 7nm 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, including a significant number of patterning steps. A state-of-the-art IC-Fab typically applies EUV for the critical patterning layers, and iDUV for the less critical layers, with mix-and-match performance of EUV and iDUV equipment to secure correct relative placement (Overlay) of each layer with an accuracy of 2.5 nm.

The reduction of line widths is a major drive in the industry, since it reduces production cost, improves performance and the quality of the manufactured products, and reduces energy consumption. Continuous increase of the device density (number of devices per unit of area) is the first business principle that makes commercial success in the semiconductor industry.

Enabled by current Deposition, Litho, Etch, Processing and Metrology tools and their performance, the 5nm technology node is about to be ramped-up by market leaders and solutions for 3nm and beyond are being explored. Given the complexity of the systems, development of new tools and equipment needs to start in time, usually some 2 IC-nodes ahead of the state of the art used in IC manufacturing. Of profound importance for the manufacturing equipment for deposition and etch technologies is the continuing search for advanced enabling materials that are required 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 as etch-stop layers or temporary spacer materials, in which case the materials might be sacrificial. The increasingly strict low-thermal budget requirements for state of the art process flows increase the challenges considerably.

Productivity improvement is 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. This can be achieved by *either* throughput improvements of semiconductor manufacturing equipment *or* process simplifications, such as moving from double patterning in DUV to single patterning in EUV. Throughput levels in DUV litho is currently 275 wafers per hour and 170 wafers per hour in EUV litho.

2.1.1.2 Assembly equipment

The *forefront* of Assembly equipment addresses 2 trends:

- In order to maximize the benefits from ICs made for IC-nodes of 7 nm and less, *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 (“VAIs”), 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.

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;
- Application for medical applications on topics as organ on chip;
- Application for Power modules/discretes for electric cars, power grids and industrial equipment;
- Integration of optical inputs/outputs in electronic IC’s.

2.1.1.3 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:

- 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;
- Salland Engineering that designs and manufactures high quality instruments to upgrade the performance or channel density of automatic test equipment (ATE) and/or Test & Measurement set-ups.[10]

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

- Needed to enable cost-effective production of 3D ICs using advanced packaging (e.g. using chiplets);
- For special ICs, like with IC-packages with integrated photonics and "lab-on-a-chip".

2.1.2 Science & RTOs

2.1.2.1 Knowledge and Technologies for Wafer-Fab Equipment

For the extremely advanced Lithography equipment, beyond-state-of-the art Knowledge and Technologies ("K&T") is generated by many thousands of R&D specialists at ASML and its *industrial/private* partners and suppliers.

For extremely advanced stand-alone Measurements Equipment, beyond-state-of-the art K&T is generated by ThermoFisher and its ecosystem for, e.g., new microscopes (using TEM/STEM/EELS/EDX [11]) for fast, sub nanometric 3D imaging and chemical analysis, and other measurement equipment to enable the development and near line process monitoring for manufacturing of sub-3nm IC-node ICs.

In addition to this private/industrial R&D,

- ARCNL develops, in a PPP, beyond state-of-the-art K&T 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 [12].
- TNO develops, in PPP's, beyond state-of-the-art K&T for Molecular Contamination Control and enhanced lifetime for EUV optics, particle contamination control for EUV lithography and assembly equipment, opto-mechatronics for new metrology, lithography and sensor concepts, acoustic metrology, Thermal & Flow solutions for iDUV, unique equipment for research and concept qualification, AI for preventive maintenance, architectures for embedded software.
- Universities and other institutes such as TU/e, UTwente, TUDelft, and DIFFER, develop with involvement of private/industrial companies beyond-state-of-the-art K&T 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;
    - 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;

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

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

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

- 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.

2.1.2.2 Knowledge and Technologies for Assembly Equipment

For the advanced Packaging Equipment, beyond-state-of-the art, K&T 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 investigating whether the most advanced packaging with wafer-to-wafer bonding for 3D, fits in its portfolio and what K&T it requires. 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.

Beyond state-of-the-art K&T also needs to be developed for assembly equipment for new package formats that supports 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.

2.2.2.3 Knowledge and Technologies for Test Equipment

Several private companies in the Netherlands develop K&I in the field of test equipment (see Section 2.1.1.3 Test Equipment). In addition, beyond state-of-the-art K&I 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.[13]

2.2 Developments in present and future markets and societal themes

The market pull in the past years came primarily from high demands for conventional consumer devices (i.p. Smartphones), related communication networks (4G, 5G) and data centers. The societal challenges as defined by Europe and the Netherlands, are expected to result in *additional* fast-growing markets for Electronic Components and Systems. The societal challenges for the Netherlands are described in the thematic KIA's ("Knowledge and Innovation Agendas"). Examples of the ECS required for the 6 KIAs are given in the next sections (3.1.1 – 3.1.6) and the Appendix (A1 – A4).

2.3 Questions and milestones for this roadmap in 2025

2.3.1 Main Questions

1. How to benefit from Public-Private Partnerships (with RVO co-funding[14]) and support of Applied Technology Projects at universities/RTOs (with NWO funding[15]) to keep on pushing the limits of key enabling technologies, resulting in semiconductor manufacturing equipment with a good business case for manufacturers of ECS, in order to respond to the large market pull for innovation?

[13] https://www.tudelft.nl/ewi/over-de-faculteit/afdelingen/quantum-computer-engineering/computer-engineering/staff/said-hamdioui/
[14] https://www.rvo.nl/subsidie-en-financieringswijzer/pps-toeslag-onderzoek-en-innovatie
[15] https://www.nwo.nl/onderzoek-en-resultaten/programmas/htsm

2. How to ensure that promising ideas, coming out of the societal KIA-1 – KIA-4, 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.[16]
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?

2.3.2 Main Milestones in 2025

- ASML (2025): Holistic Lithography enabling IC nodes below 3 nm IC-node with advanced patterning solutions with competitive wafer throughput, overlay performance and uptime.
- ASMI (2025): 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 3nm IC node), more complex device structures, new materials and more precise and conformal film deposition.[17]
- BESI (2025): Assembly equipment for advanced heterogeneous integration of systems in three dimensional functional packages and seamless integration of the assembly equipment in the automated factory. [18]
- ThermoFisher (2025): near-line TEM for process control and failure analysis for below 3nm IC-node.
- Smaller Dutch Semiconductor Manufacturing Equipment Companies, Contract Development Companies and Contract Manufacturing Companies work towards increased market shares, but did not provide Mail Milestones in 2025.

3. Priorities and implementation

3.1. Priorities of implementation

Priority of implementation will be given to R&D that fits with the Knowledge and Innovation Agenda **KIA-5** ("Key Technologies") for the Dutch Semiconductor Manufacturing Equipment industry and its ecosystems:

- To realize, defend and extend earning powers and competitive advantages;
- To support the ECS industry to manufacture the (innovative) ECS that are needed to realize solutions to meet the societal challenges in **KIA-1 – KIA-4**.

3.1.1 KIA-1: Energy transition and Sustainability[19]

The Semiconductor Manufacturing Equipment sector contributes to the Energy transition and Sustainability by: i) reducing the energy consumption of manufacturing equipment compared to their productive output, ii) enabling minimization of waste, iii) enabling maximization of the value from the materials used and repurposing products across their lifecycle, iv) enabling minimizing of power consumption of ECS, and v) enabling the manufacturing of the innovative ECS required for the energy transition. See Appendix A1 for examples.

[16] https://www.vdlgroep.com/nl/nieuws/opinieverhaal-chinese-bussen-kosten-banen-in-nederland
[17] https://www.asm.com/Downloads/2019_ASMI_Annual_Report.pdf
[18] https://www.besi.com/fileadmin/data/Investor_Relations/_Semi___Annual_Reports/Annual_Report_2019.pdf
[19] https://www.topsectoren.nl/innovatie/documenten/publicaties/2019-publicaties/oktober/161019/kia-energietransitie-en-duurzaamheid

3.1.2 KIA-2: Agriculture, Water and Food [20]

With a growing world population in combination with restrictions on the use of natural resources, Internet-of-Everything like systems will become vital for the sustainable production, management and consumption of healthy water and food. Semiconductors Manufacturing Equipment will enable many of the required ECS. See Appendix A2 for examples.

3.1.3 KIA-3: Health and Care[21]

To address the challenge of an ageing population in combination with a trend towards patient tailored medicine, electronics in the health domain is already widespread and expected to increase even further. New advances in Semiconductor Manufacturing Equipment will be essential to enable, with innovative ECS, the paradigm shift *from* large expensive diagnostic and therapeutic equipment *towards* small, disposable, minimal invasive and un-obtrusive diagnostic and therapeutic instruments and tools, and personal health wearables to improve quality of life. Examples are given in Appendix A3.

3.1.4 KIA-4: Security[22]

The value chain of electronics in Europe and the Netherlands is currently highly dependent on countries outside of Europe. Keeping a grip on the equipment needed to manufacture electronics can contribute to maintaining digital sovereignty, which in turn safeguards core values such as security and privacy. Examples of the required ECS are given in Appendix A4.

3.1.5 KIA-5: Key Technologies[23]

As also indicated in the "Meer Jaren Plan Halfgeleider Fabricage Apparatuur" (MJP-HFA)[24] the Semiconductor Manufacturing Equipment sector drives ground-breaking innovations for:

- High-performance ICs, IC-module-packages and IC-packages on boards;
- Unique value/product propositions, like currently for EUV lithography scanner, and secure ICs/IC-packages for 5G enabling European sovereignty;
- The key technologies distinguished in the MJP HFA:
    - Engineering and fabrication technologies (sensors and actuators, imaging systems, opto-mechatronics, robotics, high frequency & mixed signal technologies, cyber-physical/embedded systems, digital twinning, prediction systems, model-based design and engineering);
    - Nanotechnology (Nanoscale devices, Semiconductor devices, Nanomanufacturing, Nanomaterials, nano-contamination control);
    - Digital technologies (artificial intelligence incl. machine and deep learning, big data and data analytics, digital security, high performance computing, real-time embedded software);
    - Photonics and Light technologies (light/photon generation, propagation, modulation, signal processing, switching, amplification, detection and sensing).

These innovations result in *high-value jobs* [25] in the Dutch manufacturing industry with its suppliers and partners, and in *increased earning powers and competitive advantages*.

[20] https://www.topsectorwatermaritiem.nl/missie-landbouw-water-en-voedsel/

[21] https://www.health-holland.com/public/publications/kia/kennis-en-innovatieagenda-2020-2023-gezondheid-en-zorg.pdf

[22] https://www.hollandhightech.nl/sites/www.hollandhightech.nl/files/inline-files/KIA%20Veiligheid%20-%2020191015%20definitief_0.pdf

[23] https://www.hollandhightech.nl/sites/www.hollandhightech.nl/files/inline-files/20191015%20KIA-ST_1.pdf

[24] https://www.hollandhightech.nl/sites/www.hollandhightech.nl/files/inline-files/25%20MJP%20Halfgeleider%20Fabricage%20Apparatuur%20final%20_28Mei2019.pdf

[25] As an example: ASML had by the end of 2019 more than 10000 highly-educated technical employees in the Netherlands working in R&D.

3.1.6 KIA-6: Social Earning Capacity[26]

The focus of this KIA is on understanding and supporting the accelerated diffusion of innovations for social challenges in KIA1 – KIA5 (through upscaling / roll-out). Given i) the strong market pull of *both* innovative ECS *and* Semiconductor Manufacturing Equipment needed for innovative ECS, (ii) the excellent innovation track-record of the Semiconductor Manufacturing Equipment industry, and (iii) the rapid market acceptation of innovative ECS, this KIA-6 is off less importance for this Roadmap.

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

Implementation of the roadmap will be done in Public Private Partnerships PPPs. PPPs typically consist of Large Enterprises, Small & Medium Enterprises ("SMEs"), Research Institutes an (Technical) 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.

Developments will address:

1. 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, 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.[27]
   - Equipment for manufacturing of existing and new technologies for diversified ICs, such as ICs with integrated photonics[28], and "lab-on-a-chip" typically using special microelectromechanical systems (MEMS) devices.[29] [30]
   - Equipment for nanometer scale characterization with scanning probe, electron beam, X-ray, EUV and acoustic methods for determining geometric, thermal, electrical and chemical properties (multidimensional and multidomain).
   - Multidimensional metrology equipment suitable for 3D extensions of the devices.

2. 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.

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26 https://assets.ctfassets.net/h0msiyds6poj/2AizvwNZIuU4WFDFsJPmOj/9dcb78cc25317f47c16c1a5c69ae8c34/KIA_Maatschappelijk_Verdienvermogen__volledig__20191024.pdf

27 https://bits-chips.nl/artikel/dutch-semicon-ecosystem-is-introduced-to-minimal-fab/

28 https://www.tue.nl/en/research/research-areas/integrated-photonics/

29 https://www.utwente.nl/en/education/master/programmes/electrical-engineering/specialisation/lab-on-a-chip-systems/

30 https://en.wikipedia.org/wiki/Lab-on-a-chip

- 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).

3. Test Equipment
   - See Section 2.1.1.3.

3.3 Reference to MJP's in KIA Key Technologies [31]

The following MJPs have strong ties to the Semiconductor Manufacturing Equipment roadmap:

- 25. Halfgeleider Fabricage Apparatuur;
- 90. ARCNL;
- 09. Nano-contamination control;
- 48. AI enabled Electronic Components & Systems;
- 26. Systeemarchitectuur en Systeemintegratie;
- 34. Meer Jaren Programma Smart Industry.

These MJPs address competitive power and earning power for companies in the Netherlands and also have as explicit objective to use:

- *Either* Public-Private Partnerships (PPS) with as private partners Large Enterprises, Small and Medium Enterprises and start-ups of which at least one has committed budget, resulting in PPS/TKI allowance by RVO or European/National subsidies by RVO/EU;
- *Or* in-kind/in-cash contributions by private enterprises to PhD projects at universities, under the condition that NWO allocates budget to this.

3.4 Linkage with other innovation instruments (e.g., public purchasing and risk investment

As of today, there is no linkage with public purchasing and risk investment, but this is expected to come in view of the societal challenges in the KIAs.

3.5 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 PPP-Clusters: ECSEL, PENTA, ITEA3, EUREKA, Dutch Programs for PPS/TKI and TTW (Applied Technical Research) for HTSM;
- Leverages the Strategic Research and Innovation Agenda for ECS with a full chapter devoted to Semiconductor Manufacturing Equipment;[32]
- Is done in cooperation with Dutch companies, RTOs and universities in European Horizon 2020 Cooperation Projects;
- Is supporting the establishment of a new European PPP "Key Digital Technologies" as intended successor of the ECSEL JU for which the last call was in 2020;[33]
- Will be done in collaboration with Dutch companies, RTOs and universities in the context of the new Horizon Europe Program that is planned to start in 2021.

4. Partners and process

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

- Science and RTOs: ARCNL, TNO (i.p. in Delft and Eindhoven), TUD, TU/e, UTwente, DIFFER, CITC.

[31] https://www.hollandhightech.nl/kia-sleuteltechnologieen
[32] https://aeneas-office.org/wp-content/uploads/2020/01/ECS-SRA2020_L.pdf
[33] https://ec.europa.eu/research/pdf/horizon-europe/ec_rtd_orientations-towards-the-strategic-planning.pdf

- Public Organizations: The Netherlands: EZK, RVO, NWO, ..
- Europe: European Commission (for Horizon 2020, Interreg, Eureka with countries, upcoming Horizon Europe).
- Regions: Brainport Eindhoven, Brabantse Ontwikkelings Maatschappij, Provincie Noord Holland
- Cities: Amsterdam (ARCNL), Eindhoven.
- Industry / Private Parties in the Netherlands with activities related to this roadmap (like ASM International, ASML, Besi, Boschman, Bronkhorst High-Tech, Demcon, Domicro, Frencken, Heinmade, IBS Precision Engineering, KMWE, Kulicke & Soffa Liteq, Malvern Panalytical, MI-Partners, Nearfield Instruments, Nedinsco, Nexperia, Omron, Prodrive, Reden, SIOUX, Solmates, Solutions on Silicon, Technolution, Tegema, ThermoFischer, Trymax, VDL ETG).

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).[34] 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 and ("More Moore");
- For enlargement of functionality for (shrinked) ICs and IC-packages("More-than-Moore");
- Acceleration of manufacturing.

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

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

5. Investments

Roadmap	**2020 MEuro**	**2021 MEuro**	**2022 MEuro**	**2023 MEuro**
Industry	45.0	45.0	44.6	44.1
TNO/ARCNL	6.6	6.6	7.1	7.1
CTIC	1.0	2.0	3.0	5.0
NLR				
NWO				
Universities	4.3	4.3	4.3	4.3
Departments and regions (excluding TKI)				
Grand total	**56.8**	**57.9**	**59.0**	**60.5**

European programs within roadmap	**2020 MEuro**	**2021 MEuro**	**2022 MEuro**	**2023 MEuro**
Industry	34.7	34.8	34.3	33.8
TNO/ARCNL	2.1	2.1	2.1	2.1
CTIC				
NLR				
NWO				
Universities	4.3	4.3	4.3	4.3
EZK co-financing of European programs	8.3	8.3	8.2	8.1
European Commission co-financing	8.3	8.3	8.1	8.1
Grand total	**57.7**	**57.7**	**57.0**	**56.4**

R&D in NL-only PPPs	**2020 MEuro**	**2021 MEuro**	**2022 MEuro**	**2023 MEuro**
Industry	**10.3**	**10.2**	**10.4**	**10.3**
TNO	**4.5**	**4.5**	**5.0**	**5.0**
CITC	**1.0**	**2.0**	**3.0**	**5.0**
NLR				
NWO				
Universities				
Departments and regions (excluding TKI)				
Grand total	**15.8**	**16.7**	**18.4**	**20.3**

Figure 3: R&D in public-private partnership, including contract research; all numbers are in million euro.
Upper table: Investments in all PPPs, excl. co-funding by EZK/NL for European Programs
Middle table: R&D investments in the PPPs enabled by the Horizon2020/ECSEL program.[35]
Lower table: NL-only investments for R&D in public-private partnership, including contract research (in-cash plus in-kind contribution).[36]

The lower table was added in order to make transparent that National PPPs get significantly less investments than European PPPs, which led to the contents in Section 2.3.1 (Main Questions). In the past years, PPP investments for European project for Semiconductor Manufacturing Equipment have diminished due to reduction of maximum public (EU/NL) co-funding per project. Looking forward to 2021-2023, 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.

[35] The values were estimated by using the combined European PPP ecosystems of ASML and ThermoFisher, and by using the investment data of BESI, ASMI, Boschman and KMWE.

[36] The lower table includes investment data from the parties have shared these data (~ 40% of those asked).

Appendix: Examples of ECS required for KIAs 1-4

A1 KIA-1: Energy transition and Sustainability[37]

Semiconductor Manufacturing Equipment enables manufacturing of Electronic Components and Systems (“ECS”) required for the energy transition. Some examples are:

- Smart power electronics to enable efficient energy conversion and storage systems such as electric drives, heat pumps, electrolysers, fuel cells, batteries;
- Energy management systems controlling renewable generation, conversion & storage, on-site, in district and community grids, in regional distribution grids and by securing cross-regional transmission infrastructure, with integrated photonics enabling reliable, secure and low latency network control in future energy systems;
- Equipment (incl. for Augmented Reality) enabling remote working/meetings/education with low-power high-performance chips thereby reducing energy consumption and CO2 emission;
- High voltage applications in electric cars and windmills;
- Large area electronics of solar cells;
- Electronics for Electric Cars;
- Photonic components for low-power connections in data-centers;
- High-performance logic to enable advanced software for climate models using big-data.

A2 KIA-2: Agriculture, Water and Food [38]

Semiconductor Manufacturing Equipment will enable the required Electronic Components and Systems for:

- Food security and sustainable circular production, to ensure animal and plant health by means of innovative interoperable farming systems (including end-to-end food supply chain), and new management systems to offer to consumers better food information (including country of origin, nutritional value, and environmental footprint);
- Water resource management, to ensure access to healthy water in rural and urban areas by introducing i) smart sensors-based solution for water quality monitoring, ii) new technologies to allow smart water treatments fostering circular use of water, and iii) smart systems for flood and irrigation management;
- Environment protection to monitor, report, prevent and remediate air and soil pollution and waste, and to contribute to achieving a circular economy, by introducing advanced sensors and diagnostics for air quality monitoring (indoor, urban and rural) and smart systems to control and prevent greenhouse gas emissions;
- Efficient smart networks for remediation in different ecosystems (water bodies, air, and soil).
- New advanced (bio-)sensors and (bio-)actuators, ubiquitous low-cost direct monitoring of air and water quality (CO2, NOx, CxHy , small particles, …) through on-chip spectrometers and fiber-tip detectors;
- Artificial Intelligence for massive Big-Data-based interoperable systems-of-systems to facilitate evidence-based decisions and expand the capacity to understand and tackle environmental challenges.

A3 KIA-3: Health and Care[39]

New advances in Semiconductor Manufacturing Equipment will be essential to tackle with innovative Electronic Components and Systems the bottlenecks in health platforms from (multi) hospital level to personal wearables to improve quality of life. Some examples are:

[37] https://www.topsectoren.nl/innovatie/documenten/publicaties/2019-publicaties/oktober/161019/kia-energietransitie-en-duurzaamheid
[38] https://www.topsectorwatermaritiem.nl/missie-landbouw-water-en-voedsel/
[39] https://www.health-holland.com/public/publications/kia/kennis-en-innovatieagenda-2020-2023-gezondheid-en-zorg.pdf

- Miniaturized healthcare for diagnosis and implantation with miniaturized low-power electronics with sensors and actuators;
- Personalized medicine enabled by high-performance computing (and in future Quantum Computing) to reduce ineffective treatments and improve patient outcomes, thereby reducing waste in resources;
- Healthcare digitization with remote diagnosis/care/education/meetings to reduce greenhouse gas emissions;
- Secure digitized healthcare promoting behavior change, in a context of ageing population, to reinforce prevention impact and disease control, and to reduce the number of chronic diseases;
- Pandemic control systems.

A4 KIA-4: Security[40]

Examples of the required ECS are:

- Secure chips or chip-packages made in the Netherlands/Europe;
- Secure, high-speed, edge/cloud and edge/edge communication for remote working/education/diagnosis/care/meetings, and for mobility applications (like intelligent traffic systems and autonomous driving solutions), with secure chips and secure chip-packages;
- Made-in-Europe security for high-performance advanced defense systems.

[40] https://www.hollandhightech.nl/sites/www.hollandhightech.nl/files/inline-files/KIA%20Veiligheid%20-%2020191015%20definitief_0.pdf