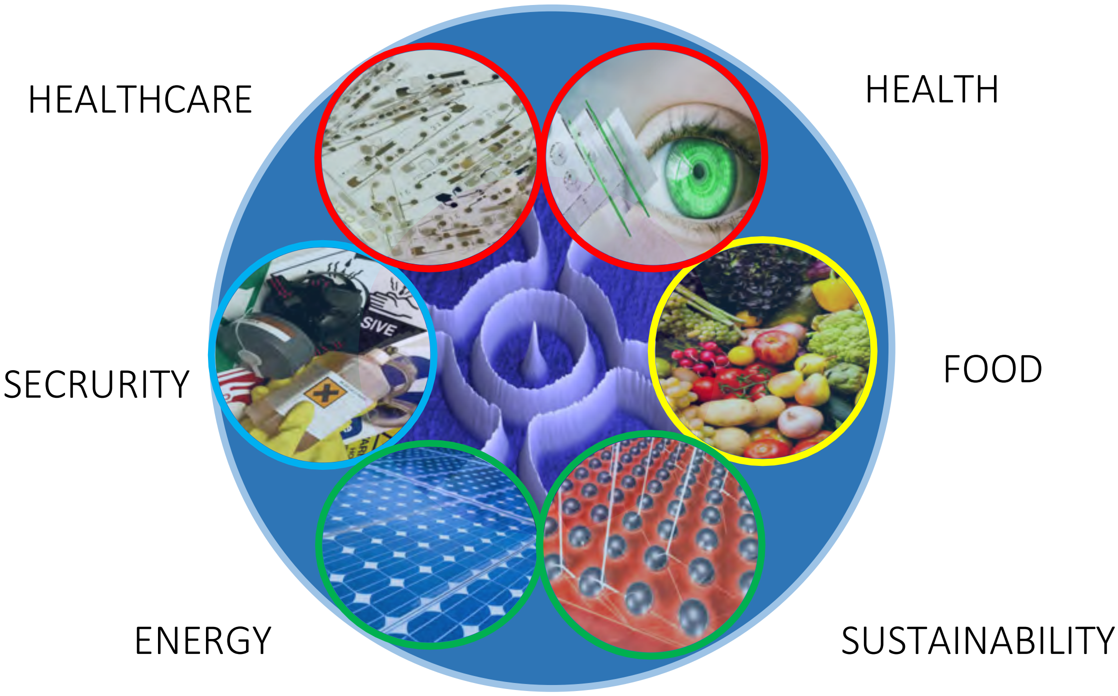
DUTCH ROADMAP NANOTECHNOLOGY



PROLOGUE

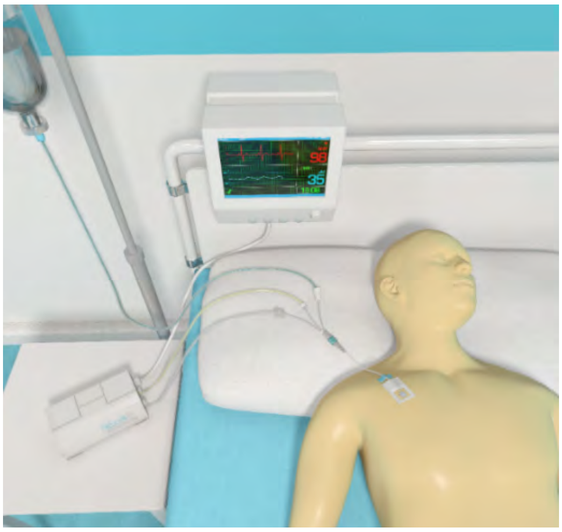
Nanotechnology is considered a key technology. This roadmap describes the multi-year plan to bring this key technology to a higher level. In order to achieve this, the entire value chain has been involved and described, from science to spin-off and start-up, from SMEs to large companies and of course also the end user.
This roadmap provides a vision for development by connecting scientific agendas to societal challenges. Social relevance is emphatically integrated into it, because socially responsible innovations can only be successful through collaboration between science and business.

In particular, this roadmap describes how the Netherlands can maintain its leading position in nanotechnology on the international playing field.

The Netherlands has opted for 4 main themes in which nanotechnology can play a key role in meeting societal challenges:
1. Health and healthcare,
2. Energy and sustainability,
3. Agriculture, water and food,
4. Security.
All these themes are in line with the European Green deal.

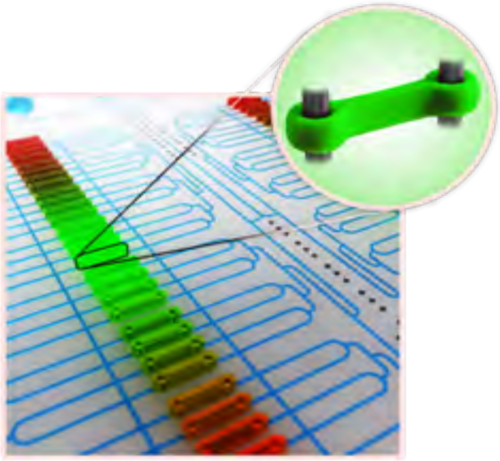
SOCIETAL CHALLENGES AND ECONOMIC RELEVANCE

Nanotechnology is at the stage where the industry-wide implementation of this technology is approaching, safety has to be guaranteed, and, more than ever, social acceptance is a fact. Future questions that arise, while speculative, are how nanotechnology can help people to live longer, safer, more sustainable, and healthier? When and how will the quantum computer make its appearance? Can we securely communicate on long distance with quantum technology? Are newly manufactured materials smarter than natural ones, with the ability to adjust to situations, heal themselves, or are they so intelligent that they fully adapt to the circumstances or provide us with full renewable energy? Will the food production become effective as well as with lower impact on the environment that the expected shortages will be ancient times? Is our safety guaranteed by a conditioned environment? How can nanotechnology help to beat the COVID19 pandemic (vaccines, medicines, fast and cost-effective testing), and on longer term: how can the next pandemic be prevented? Or can we reduce cancer mortality rate to nearly zero? These are all questions to which there are no ready-made answers. It is clear that the innovation of technology will play an essential role. Nanotechnology, as one of the key technologies, delivers a significant contribution to the following challenges.



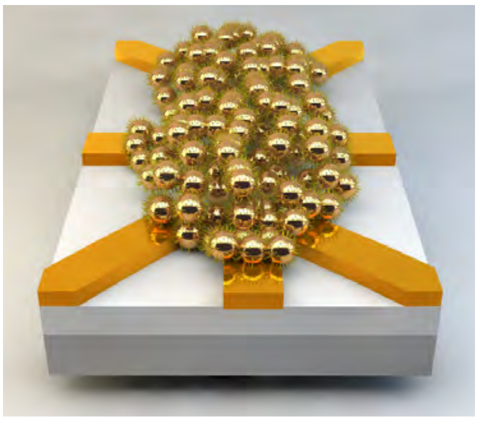
COVID-19 patient Cytokine Storm monitoring (TU/e)
Developing a biosensing technology, based on Biosensing by Particle Mobility for the continuous monitoring of patients. Focus is on monitoring the inflammatory markers, which is crucial for patients who are at risk of Cytokine Release Syndrome or Cytokine Storm.

Within healthcare we look for solutions to give people a better quality of life and to take care of yourself becoming elderly through tailor-made care. The lab is expected to take place even more in people's homes instead of people going to the lab. Medication and therapy can be performed by microfluidics and nanotechnology-based lab-on-a-chip solutions, which are more adapted to the individual (personalized medicine). Nanotechnology-based DNA analysis systems are used to analyze the entire genome, but also gut flora, cancer cells and much more. Organ-on-a-chip is expected to accelerate drug development and personification, and to reduce animal testing. Nanotechnology improves targeted drug delivery and contrast media for imaging techniques. Nanomechanically tuned materials and structural properties reduce implant rejection processes, and enable portable medical measurement and monitoring instruments that are patient-friendly. These materials enable also efficient minimally invasive surgical instruments that reduce intervention and recovery time, both contributing to reduced health costs.



Organs-on-Chips for better COVID-19 treatment (hDMT)
Why does the disease lead to such serious complications in one patient, but not the other? What is the most promising target to develop a new drug? Are there new types of treatments that are potentially effective? And are such experimental treatments actually safe? In order to quickly provide answers to these questions, organ-on-chip studies that realistically mimic the patients' bodies will be utilized. Heart-on-chip with rows of miniaturized heart tissues in a microfluidic chip with integrated sensors.

How do we ensure a sustainable energy supply in the future? Can we increase the efficiency of solar cells up to their theoretical limit? Can we beat this theoretical limit by adopting nanotechnology solutions? Can we reduce the capacity and weight of batteries by a factor of 5 or 10? Should we move towards radically new nanoquantum concepts such as "spin batteries" that can in principle be charged and discharged indefinitely with an almost unlimited energy content? Closer to present day are innovative nano-electrochemical breakthroughs possible to make hydrogen or basic chemical compounds from sunlight or electricity. Nanomaterials will provide solutions for faster, safer and lighter batteries at industrial scale. A completely different area is Brain Inspired Computing, where the superb energy efficiency of the human brain serves as a paradigm for completely new innovative computing concepts including nanotech based multi-dimensional networks.

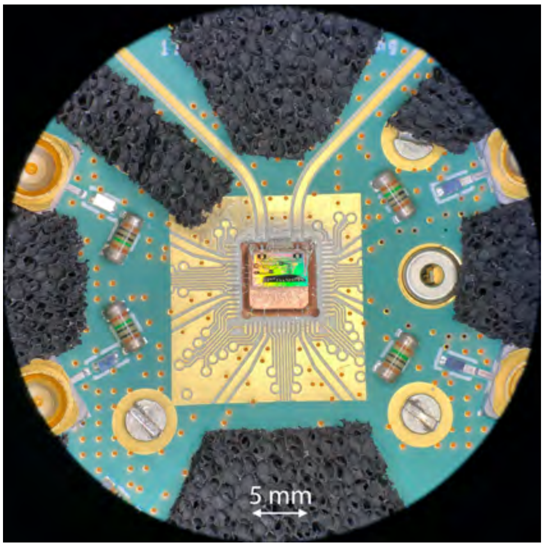


Classification with a disordered dopant- atom network in silicon

*Artistic impression of stacking of nano-particles with organic molecules which form a network. Wilfred v.d. Wiel group Nature **577**, pages 341–345 (2020)*

Healthy food and clean water are essential for people's health and well-being. However, it must be tailored to the body's needs, individual preferences, and produced sustainably. Process innovations based on nanotechnology, such as membrane technology in separation processes, lead to more sustainable and circular production. Nanostructured ingredients, nutrients, and pesticides ensure a better release and, therefore, less waste and side effects. All this finally leads to optimal food quality and safety, less food waste, and sufficient and pure water for the consumer with the smallest possible ecological footprint. Food is a nanostructured material and its processing in the body also takes place on a nanoscale. That is why the opportunities of nanotechnology are used to realize better product properties and/or new functionalities ("Food / body interaction") that fit into a preventive care concept. Nanotechnology based sensors will provide new methods for nutrition level monitoring of healthy beings and process monitoring in food industry. Nanotextured and catalytically active surfaces enable removing or breaking down critical contaminants during waste water treatment and recirculating them as feedstock for new chemical products.

How do we get a grip on the advancing digitization and how do we prevent unencrypted data from falling into the hands of others? Do we, as citizens, have control on the multitude of medical data that is generated and that is growing? Can we protect our own DNA code? In many cases, future nanotechnologies offer the solution. Here, nanotechnology-based data encryption will play an important role, as will nanobiosensors that can identify viruses or micro-organisms extremely fast. Nanotech based solutions will provide DNA data storage and readout methods.



Chip design for quantum computing

Optical microscope image of a quantum chip with nanostructures connected to a printed circuit board. (QuTech)

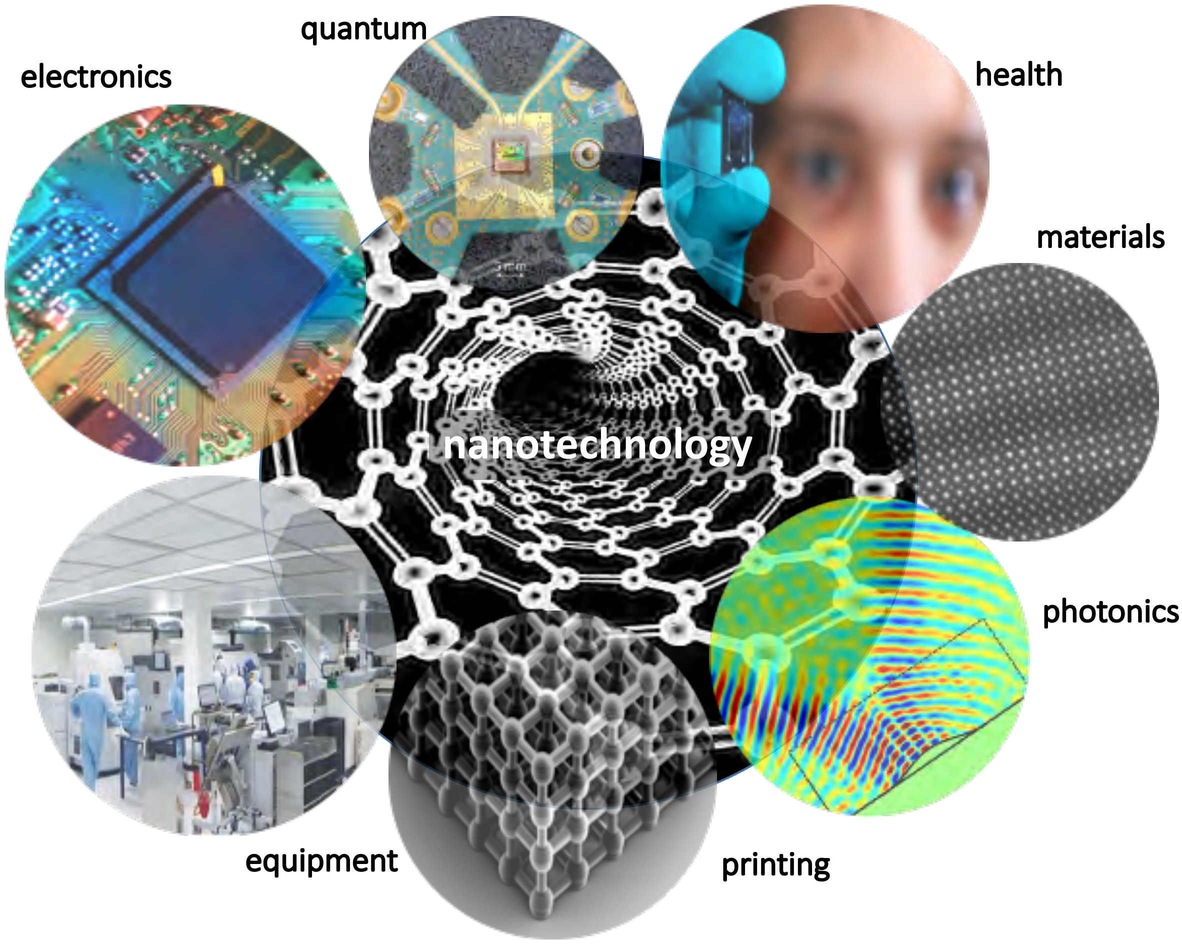
The emerging field of quantum computers, accomplished with nanotechnology, will contribute to the acceleration of the technology push needed for all kind of social challenges by creating a leap forward in the ability to solve complex problems. Such exponential growth in compute power cannot be achieved by the most advance conventional super computers. Nanotechnological developments for quantum computing and quantum internet will, for example, provide a data processing and is expected to provide a better understanding of complex systems in healthcare, diagnostics, food processing, disease modelling ect..

ECONOMIC RELEVANCE

The companies and institutions that make use of (new) technological progress based on nanotechnology mainly operate in international markets that are in line with the mission and challenges of the Dutch economy. These global markets, in which nanotechnology plays a key role, are worth billions of Euro's with realized but also expected growth rates of more than 15% (CAGR). Many companies (large enterprises and SME's) use nanotechnology as an enabling, and often differentiating, technology in their R&D, production processes and/or production. These specifically include most of the large innovation-intensive companies in the Netherlands, playing an important role in High-Tech (e.g., ASML, Philips, NXP, Thermo-Fisher, ASMI and Malvern-Panalytical), Food (Friesland Campina, Unilever, Danone), Chemistry (DSM, Akzo) as well as Healthcare, Pharma and Life sciences (Philips, Janssen Pharma, Roche, Galapagos). It is difficult to give an economical value to the nanotechnology-related revenue of these large companies, as they are typically not selling nanotechnology (products) per se, but equipment, chemicals, medicines etc. which then fall into other business categories and sectors (see figure below). The other way around, the large industries play an important role in the nanotechnology environment working with medium sized deep tech companies and government, and co-funding advanced science at universities and other institutes in the well-known triple helix.

For the field of quantum-nano, a couple of large international companies are investing (Microsoft, Intel) into the Dutch ecosystem. Anticipating the huge impact of quantum computing and quantum communication, also several Dutch companies (KPN, ABN-AMRO) are getting involved in applications.

High-tech SMEs able to carry out multidisciplinary projects in collaboration with knowledge institutions, large companies and societal organizations, form a second driver for the growth of this sector. The estimate of the historic growth rate of the Dutch ecosystem is above average for the nanotech sector. Patent filings and publications have been in the worldwide top 15 over the past decades.



Nanotechnology roadmap with important connected HTSM roadmaps

The current estimated export potential of just the SMEs (<250 FTE) is estimated at more than 1 Billion Euro. There are currently approximately 8000 employees working at the nano-related HT-SME's that provide products and services that would not have come about without the key enabling nanotechnology.

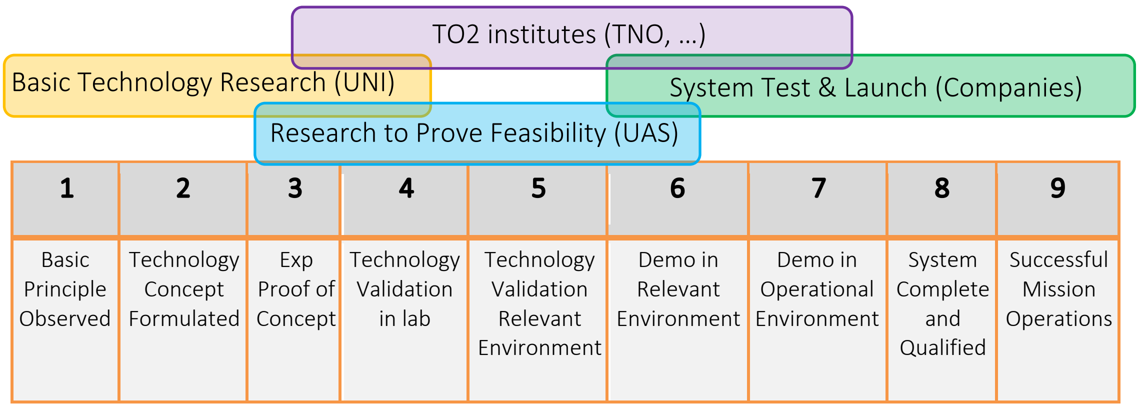
By making the right investment that is well balanced to create a flow from research to industry to impact, a large increase in impact can be expected and with it the earning capacity of the Netherlands. This increase is achieved through a mission-driven, widely supported national approach that support every part in the chain in such a way that none of the elements of the chain is weaker than the other.

The resulting ecosystem has resulted in a large number of HT-SMEs with scaling-up potential and a good basic infrastructure that make the chances of economic impact very high.

Key Enabling Technologies, like nanotechnology, are thought critically to reach some of the transitions and goals of the European Green Deal, like in health care, in solar and battery technologies, and many more. However, the adequacy of safety regulation for nanotechnology is still under debate. Appropriate risk governance shall be proportionally pushed, to create optimal impact from the investments in technology development. Build on the foundations of NanoNextNL in developing an organisation and activities at synchronicity regarding safety, regulation and standardization with investment and innovation and with dialogue with societal partners and international cooperation must be continued.

Due to the regularly human-oriented applications of nanotechnological products, there is a great demand for thorough research, validation, and risk assessment and management. These are necessary to convert an innovation into a marketable and approved product. Timelines of 15 years of research and development are the rule rather than the exception.

HighTech companies involved have a great willingness to invest. Economic impact from nanotechnology is already realized by the industry, quite a few applications have successfully moved to higher *Technology readiness levels* (TRL). In addition, there is a multitude of innovations available that can be quickly taken to higher TRL through rational step-by-step policy. A policy that can be achieved with investing in public private partnerships. Focus on products from private partners is expected at TRL beyond 6, with an expected time to market of 5-10 years.



Technology Readiness Levels and the corresponding expertise fields of universities (UNI), universities of applied sciences (UAS), TO2 institutes, and companies.

To create a flow from idea to impact the instrumentation supporting public private partnerships should be well balanced across all TRL levels. The TRL levels of different concepts and technologies differ. Quantum related technologies are at the lower end of the TRL levels, Nanotechnology for MEMS and semiconductor applications are for example a the higher TRL levels. Every innovation starts at level 0. The time to impact depends on the already existing ecosystem and infrastructure present.

SOCIAL IMPACT:

In the field of sustainability, society has to adapt to new standards. The climate agreement provides guidelines that cannot be achieved without the innovative contribution that nanotechnology offers us. Using energy more consciously and more efficiently shows that other forms of energy supply are needed.

The sector will work on standards that have a positive influence on people and nature. The entrepreneurs and ministries in this sector are joining forces at this point and the willingness to invest in high-tech solutions is significant.

Nanotechnology increasingly contributed to the earning capacity of the Dutch industry in the past and the above outlined opportunities enable a significant growth of its economical contribution to the wellbeing of the society in the near future.

APPLICATIONS AND TECHNOLOGIES

The following applications are not exhaustive, but do provide a good illustration of the applications and challenges for nanotechnology in the various societal challenges.

HEALTH AND CARE:

- Personalized medication with lab/organ on a chip enabled by nanofabrication and microfluidics technology;
- DNA analysis and synthesis techniques based on nanopores and nanomachines;
- Self-management by (home) health monitoring enabled by nanotechnology detectors (wearables, insideables, disposables); based on nanophotonics and nanoelectronics;
- animal as well as animal-free testing for drug development enabled by nanotech based Organ on a chip;
- targeted drug delivery enabled by nanofabricated particles and needle;
- Enhanced (medical) imaging by nanoparticles and detectors with higher resolution enabled by nanofabrication;
- Virus (SARS COV-2) related research, like virus detection, antibody research, drug delivery and vaccine development; enabled by nanomaterials, nanophotonics, and microfluidics.

ENERGY AND SUSTAINABILITY:

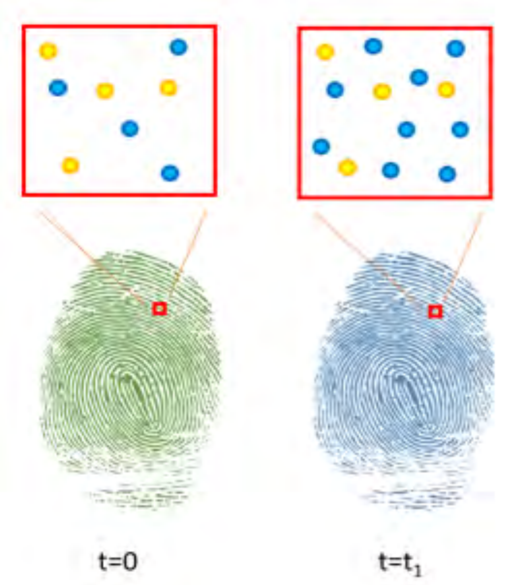
- energy conversion enabled by nano-electrochemistry and nano-structured surfaces;
- batteries and solar cells enabled by nanolayers, nanomaterials and nano-patterned surfaces;
- CO_2 capture enabled by Nanomembranes;
- Low energy consumption electronics (Green ICT) enabled by next-generation electronics and photonics based on nanotechnology.

AGRICULTURE, WATER AND FOOD:

- sustainable food production and monitoring of food products by nanosensors.;
- modulation of the properties of ingredients on the nanoscale;
- efficient absorption of food, management of allergies and digestive problems by understanding food body interactions at the nanometer scale, and 3D nano-printing;
- water filtration by means of membranes with nano-patterns and structures;
- Environmental monitoring with nanotechnology based sensors (drugs, pollution, viruses, etc..);
- Remote sensing with drones and satellites with nanotech based sensors.

SAFETY:

- quantum computing and encryption enabled by qubits built with nanofabrication (new materials, new patterns, new architectures) and nanoscale connectivity &electronics;
- data storage technology (DNA encoding) enabled by nanofabrication, and readout by nano sensors like nano-molecular motors;
- Safe-by Design: risk management, risk analysis and toxicity of nanotechnology;
- forensics research at the point of crime enabled by nanotech based sensors.



Dating fingerprints with quantum nanodots

Dating fingerprints using two different quantum dots (QD) with different wavelength. When the acidity changes, the associated concentration of the QDs will lead to a different ratio of color and, therefore, characteristic how long ago the fingerprint was applied. (Saxion)

SAFETY, REGULATIONS & STANDARDIZATION:

- development of a risk governance system keeping pace with modern innovation policies (integrated innovation system), risk governance in support of valorization of knowledge (from science to test guidance and test guidelines);
- Safe-and-Sustainable-by-Design tools.

TECHNOLOGIES:

Technologies needed for Nanotechnology can roughly be divided in:

- NANO FABRICATION AND TESTING INFRASTRUCTURE
- NANO MANUFACTURING
- NANO INSPECTION AND METROLOGY
- NANO MATERIALS, PROCESSES AND PRINCIPLES
- SOFTWARE, CONTROL, AND ALGORITHMS FOR NANOTECHNOLOGIES,

NANO FABRICATION AND TESTING INFRASTRUCTURE

Most nanotechnology processes need very specialised environments that are super clean and conditioned to enable the research, development, and manufacturing of nano-based devices. These cleanroom environments are crucial infrastructure to be able to work on nanotechnology. The main source of pollution in a cleanroom is a human being. This is why people are suited up in special gowns to prevent humans contaminating the nanostructures.

Cleanrooms and the equipment within them as well as their very specialised supporting staff are crucial infrastructure for research and manufacturing. Institutes, start-ups, scale-ups and multinationals like NXP and ASML all need cleanrooms to work on nanotechnology subjects. The whole supply chain needs to work every time cleaner to keep up with constantly reducing feature sizes and increasing quality demands to enable for instance reliable qubits or nano sized sensors for automotive. Open access cleanrooms for research and development that are shared with companies are organized within NanoLabNL.

NanoLabNL plays a central role in research, development and the embedding of nanotechnology. Equipment and expertise are available at the six locations for nanoscale manufacturing of microreactors, MEMS, micro-structured materials and membranes, and electronic and optical components for diverse applications. There are also diverse facilities available at the six locations for general nanoscale fabrication. In addition, each facility offers unique equipment and expertise for items like the fabrication of *quantum and photonic devices,* surface analysis, lithography, and microfluidics. This approach, with facilities being geographically dispersed and complementary, has proven to be particularly effective.

NanoLabNL is a collaboration of six laboratories spread across five locations. In Amsterdam- the AMOLF institute; in Delft the locations are the Kavli NanoLab and the Else Kooi Lab of TU Delft and the Van Leeuwenhoek Laboratory of TNO as an associated partner; in Eindhoven the NanoLab @ TU/e of Eindhoven University of Technology; in Enschede the MESA + NanoLab of the University of Twente and in Groningen the Zernike NanoLab of the University of Groningen.

NanoLabNL has also taken the initiative to set up the EuroNanoLab consortium, which provides the facilities for research and links the development of key technologies in Europe. The ultimate goal is a Europe-wide infrastructure for nanotechnology, in which the participants each expand their own expertise and make it available to others. This way, they enlarge the spectrum of possibilities and technologies multiplying the societal and economic relevance and impact.

NANO MANUFACTURING
Deposition, patterning, etching, and other processing equipment
(ASML, Solmates, ASMI, VSParticle, etc..)
The nanomanufacturing has overlap with semiconductor equipment as the equipment is also operating at the nm scale and producing nm-sized device features. In addition, a lot of the equipment used for semiconductor processing can be used after some modification for other processes.

NANO INSPECTION AND METROLOGY
Scanning probe microscopies, electron microscopy, Xray analysis, advanced optical microscopies new measurement methods, quantum testing, etc..
(NFI, Smartip, Thermo Fisher, Delimic, Denssolutions, Malvern-Panalytical, …)
Progress in nanotechnologies requires inspection and metrology technologies which enable us to monitor the structure of devices at the atomic scale. On the other hand, inspection methods and equipment can only be developed and its data interpreted, if we understand the probe (sharp tip, light, electrons)-material interaction at the atomic scale as well, which can be learned from nano-science. In this way nano-science, nano-fabrication, and nano technology inspection and metrology equipment (which partially overlap with semiconductor equipment) are closely connected.

NANO MATERIALS, PROCESSES AND PRINCIPLES
Nano-structured materials, or nano-materials for short, are a series of materials that have unique functionalities or characteristics due to nano-meter sized structures in the materials. Examples vary from mirrors for extreme ultra-violet light built up from many layers of material, each only a few nanometers thin, which enable EUV lithography (ASML's latest platforms), to products with nanometer

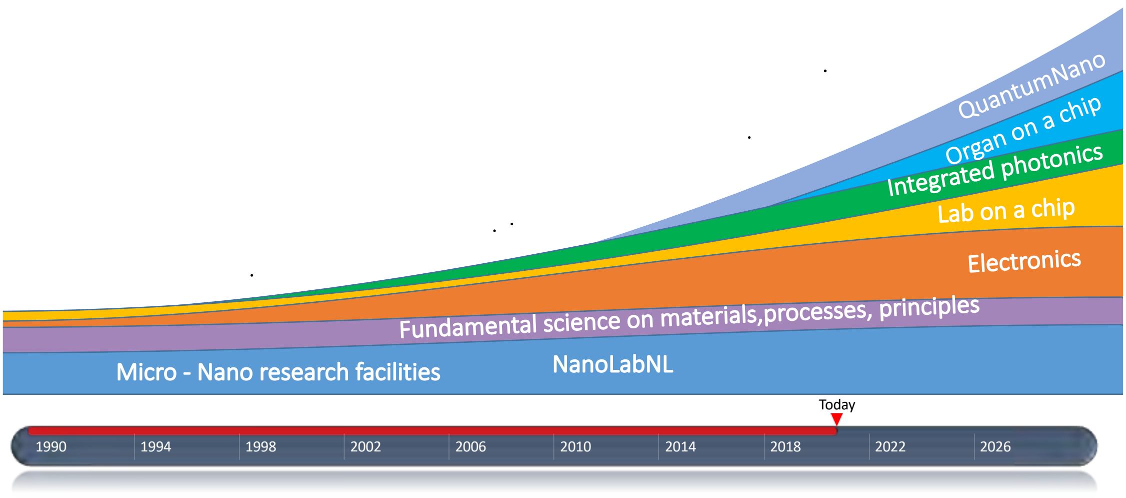
sized structures on their surface to prevent micro-organisms and bacteria to adhere, which enable sterile applications.

SOFTWARE, CONTROL, AND ALGORITHMS FOR NANOTECHNOLOGIES,
Chemical and physical processes at the nanometer or nano-liter regime are very delicate and require extreme control over the conditions, to drive or study them. For example, qubits require extreme control over the local magnetic field and the electrical signals to them, and micro-fluidics requires tight control over fluid volumes, timing and temperatures to trigger the chemical reactions we aim for. All nano-technologies require extreme cleanliness during manufacturing. Such challenges in the nanotechnologies require unique electronics and software, which cannot be found elsewhere. On the contrary, enhancements in electronics and software to control nano-processes are frequently the basis for new developments in such products and markets. Algorithms and software that are needed for the functionality of the nano hardware are in scope of the roadmap.

PRIORITIES AND IMPLEMENTATION

Nanotechnology has been declared a priority by the Dutch government. The nanotechnology roadmap implementation has the typical characteristics of a key enabling technology. Without nanotechnology there would be no solution, product or service realized, but the technology is in almost all cases inside the solution and barely visible. Even though the nanotechnology content of the development of new solutions can be small in terms of R&D percentage, its contribution is key to the realization of the results.

The nanotechnology ecosystem is one of the strongest ecosystems in the Netherlands and well connected within Europe. It was built during the last decade out of a strong partnership between public parties now mostly represented by NanoNexNL and private parties of which most are part of MinacNed and is well connected with the larger industrial partners. These parties work in close collaboration with NanoLabNL that takes care of a large fraction of the necessary infrastructure for the ecosystem. The whole ecosystem is well connected and embedded within HTSM.



NANO INSIDE: emerging applications of nanotechnology in different areas over time

ROADMAP CONNECTIONS WITH MJP KET'S

No.	*Reference to MJP's in KIA Sleuteltechnologieen*		
10	**Nano4Society**		
91	Nano engineering		
7	Nationale Agenda Quantum		
27	Composiet		
31	Duurzame geavanceerde materialen		
32	Materials innovations (Brightlands MC)		
82	Materiaaltechnologie - made in Holland		
76	**Nano4AgroFood&Water**	**78**	**Nano4Security**
4	High Tech to Feed the World	12	Atomic Scale Processing: an enabling nanotech
13	Smart personalized food and medicine	18	Flexible electronics
77	**Nano4Health**	69	Chemische recycling
2	Building Blocks of Life	70	Katalyse en procestechnologie
9	Nano-contamination control	71	Meet- en Detectietechnologie
11	Atomically controlled magnetic meta-materials	72	Evidence Based Sensing
13	Smart personalized food and medicine	73	Soft Advanced Materials (SAM)
16	MedTech	**79**	**Nano4SustainabilityEnergy**
17	Biomedical Engineering for Health	5	Solar energy for the circular economy
43	Vitality, lifestyle & ageing in Smart Cities	6	Verbetering van de fotosynthese-efficiëntie
50	Observeren van de aarde vanuit de ruimte	36	Energy and Sustainability
60	Monitoring klimaat, gezondheid, biodiversiteit	83	National photovoltaics research initiative
74	Chemical Technologies for Medical Innovations	85	Materialen en Architecturen voor energie-efficiënte ICT
80	Nature Based Technology	93	Photovoltaic Technology" (Solliance)
86	Bridge - Life Science Technologies		
92	Medische Isotopen		

PARTNERS AND PROCESS

This roadmap was created with a broad ecosystem of companies and institutes throughout the Netherlands. During 2019 a nanovision for 2030 (**nano4society**) was created with the input that was gathered in workshops throughout the year. The sessions where organized by the trade organisation for nanotech companies MinacNed in cooperation with NanonextNL and with input from NanoLabNL. Early 2020 the synergy with Quantum technologies was identified and aligned in the Quantum Delta NL program in which nanotechnology plays a key role for the realization of the hardware components of the quantum computers, communication devices and sensors. The input from SME's was gathered in several sessions and the nanovision was presented on the international micronanoconference in 2019. An update of this nanovision was created halfway 2020 when it became clear that several initiatives like Viralert had led to new relevant activities in relation to fighting a pandemic in society. In the third quarter of 2020 the latest input has been incorporated in this updated roadmap by inviting the nanotech ecosystem delivering input. Beginning October, a concept roadmap has been published for review by the community after which it has been made final by the Roadmap team.

The Roadmap team will determine on a yearly basis if significant changes to the roadmap need to be made and will then update it accordingly.

Nanotechnology has a history with various partners, partly due to the research programs NanoNedNL, NanoNextNL and MicroNed. A selection of the partners:

(Nanotechnology) initiatives	NanoNextNL, MinacNed, NanoLabNL, TopFIT, OnePlanet, hDMT (organ on a chip), HighTech to Feed the World (HT2FtW).
Knowledge institutes	4TU's, Radboud, RUG, AMOLF TO2 institutes (TNO, Holst Centre, QuTech, etc.), Saxion, Fraunhofer, RIVM.
Governments	Holland High Tech, HTSM, Ministries, ROM's, Chamber of Commerce
Private parties	company members MinacNed and NanoNextNL, like ASML, Friesland Campina, Lionix, Micronit, NXP, Malvern Panalytical, Philips, Shell, Thermo Fisher Eindhoven, Unilever, 90+ MKB.

INVESTMENTS

Roadmap (*M€*)	2020	2021	2022	2023
Industry[1]	140	150	160	170
TNO	4	4.5	5	5
NLR				
NWO[2]	25	25	25	25
Universities/UAS	20	20	20	20
Departments and regions	15	15	15	15
Grand total	204	210	225	235

[1] Invest of SME's (<250) is M€100, with a yearly increase of 10%. About 10% is available for PPP.
[2] The NWO budget will be granted on project bases through different NWO grant schemes, in competition with other fields. The budget is estimated based on historic trends in the distribution of granted projects along the research themes in this roadmap in comparison to other themes.

European agenda within roadmap*	2020	2021	2022	2023
Industry				
TNO	2	2	2	2
NLR				
NWO				
Universities/UAS	4	4	4	4
Co-financing of European programs	2	2	2	2
European Commission				

Blank fields: data not yet available.

November 2020