# Evaluation 2014-2016

## ARCNL

### Advanced Research Center for Nanolithography

Amsterdam, 14 November 2017

Netherlands Organisation for Scientific Research

dialogic innovatie • interactie

Birch

# Content

# 1 Introduction

## 1.1 Scope and context of this review

This evaluation concerns the research carried out at the Advanced Research Center for Nanolithography (ARCNL) since its establishment in January 2014. The evaluation was commissioned and organised by the Netherlands Organisation for Scientific Research (NWO) and supported by Dialogic Innovation & Interaction and Birch Consultants.

The external evaluation follows the Standard Evaluation Protocol 2015-2021 (SEP, amended version September 2016). It is the protocol for research assessment in the Netherlands as agreed upon by NWO, the Royal Netherlands Academy of Arts and Sciences (KNAW) and the Association of Universities in the Netherlands (VSNU). The primary aim of the assessment procedure is to reveal and confirm the research quality, relevance to society and viability and to provide recommendations to improve these aspects. In addition, the procedure includes considerations with regard to PhD programmes, the research integrity and diversity of the (scientific) staff. Sections 1 and 2 of this report were prepared by NWO and do not represent input from or conclusions by the evaluation committee.

An international Evaluation Committee was established and asked to produce a reasoned evaluation of the institute and its research programmes, in accordance with the SEP. Prior to the external evaluation, ARCNL submitted a self-evaluation document covering the period 2014-2016 including a strategic forward look. This report was approved by the NWO Executive Board on 5 July 2017. The self-evaluation report and addendum included a SWOT analysis and a full set of statistics at institute and programme level concerning input (finances, funding and staff) and output (refereed articles, books, PhD theses, conference papers, publications aimed at the general public, and other output) for the three years prior to the evaluation. A number of tables were included about research staff, main categories of research output, funding, and PhD candidates (see SEP appendix D, D3). The self-assessment report therefore offered a concise picture of the institute and research groups' work, ambitions, output and resources in accordance with the guidelines provided by the SEP. A site visit formed an important part of the evaluation and included interviews with the management and Governing Board of the institute, the scientific group leaders, other levels of staff, external stakeholders and a tour of the laboratories and facilities.

## 1.2 The Evaluation Committee

The Evaluation Committee was appointed on 20 September 2017 by the President of NWO Executive Board, Prof. dr. C.C.A.M. (Stan) Gielen. The members of the Evaluation Committee were:

1. Prof. dr. Ellen Williams, Chair (USA)
2. Prof. dr. ing. Dave Blank (NL)
3. Prof. dr. Robert Brainard (USA)
4. Prof. dr. ir. Joseph Braat (NL)
5. Prof. dr. Hans Hertz (SE)

A short curriculum vitae of each of the members is included in Annex 1. The Committee was supported by Miriam Roelofs from NWO and Daphne den Hollander from Birch Consultants.

Before the site visit all members of the Committee signed the NWO Code of Conduct, by means of which they declared that their assessment would be free of bias and without regard to personal interest, and that they had no personal, professional or managerial involvement with the institute or its research programmes and that all members of the Committee would be obliged to keep the information and materials with regard to ARCNL confidential. It was concluded that the Committee had no conflicts of interest.

## 1.3 Data supplied to the Committee

On 24 July 2017, seven weeks prior to the site visit, the Evaluation Committee received the self-evaluation report and strategic plan of ARCNL, together with the draft site visit programme and an accompanying letter. The documentation also included the Terms of Reference for this evaluation; the SEP protocol; Code of Conduct; Valorisation indicators, list of panel members and supporting documentation about ARCNL.
Background information on ARCNL included the original Bid book submitted to ASML; the IPP programme and the CWTS Bibliometric report. Together, all the information required by the SEP as well as by the additional questions raised by NWO were provided on 24 July 2017. Additionally, on September 15 two additional documents were provided upon request of the committee chair:

- Research Plan Contact Dynamics Group
- Data management Policy AMOLF/ARCNL

During the pre-meeting on the first day of the site visit, the Committee was informed about the Dutch science policy and the organisation of scientific research in the Netherlands, about (the transition of) NWO and the governance structure of the NWO research institutes.

Also, on Wednesday 21 September 2017, the Committee received, on request of the Chair, additional documentation:

- Appreciation Report ASML 2017 + response letter ARCNL Director
- Collaboration Agreement ARCNL-ASML-UvA/VU - FOM
- Sketch of laboratory outline and equipment
- SAC report 2014 + response letter ARCNL Director
- SAC report 2016 + response letter ARCNL Director
- SAC report 2017 + response letter ARCNL Director
- An Output list – updated until September 2017 (includes scientific publications and patent applications)
- Photo impression of the large renovation to prepare the site in the Amsterdam Science Park for the temporary office building and to prepare the PiMU lab for the ARCNL experiments.
- List of equipment (in Dutch)

Also, some individual Panel members approached ARCNL group leaders prior to Site visit, in order to obtain specific information on the scientific work that they have completed to date. The panel thought this was very generally described in the Self-evaluation document.

## 1.4 Procedures followed by the Committee

The Committee proceeded in accordance with the Standard Evaluation Protocol 2015-2021. The overall evaluation was based on the ARCNL Self-Evaluation report; Strategic Plan and the other documentation provided by NWO, by ARCNL, and in the meetings and the interviews. Also, the lab tour was instrumental in giving the Committee insight into operations.

All meetings, the lab tour and the interviews took place during the site visit made from 20-22 September 2017. The programme of the visit is included in Annex 2.

A first pre-meeting between the two secretaries and the Chair was held on 3 July 2017. Topics were the SEP Protocol (in brief); the Site Visit; time schedule (process) and preparation of a pre-meeting with the Committee (via Video connection). The pre-meeting of the Committee was held on 5 September 2017. Items on the agenda were: introduction; site visit programme; division of tasks; format of the evaluation report.

The Committee met on the afternoon and evening preceding the site visit. The afternoon meeting was used to meet the President of NWO; to discuss the evaluation criteria and rating as well as the Dutch research landscape. Also, the site visit programme was fine-tuned and preliminary issues and questions were discussed in brief.

During the site visit, all interviews and sessions (i.e. meetings with the Governing Board; the Scientific Advisory Committee, Management, etc.) were conducted by the entire Committee. One exception was the interviews with the PhD students. The panel was split up and each individual member had a chance to speak to 4 students, in two rounds of 20 minutes.

At the end of day two, on Friday 22 September, a meeting was held with ARCNL Director, Manager of Operations and Secretary (Jasper Reijnders) to the NWO Executive Board to present preliminary findings.

On Friday 20 October, a draft version of this report was sent to ARCNL Director for factual correction and comments. The report was subsequently submitted to the NWO Executive Board.

## 1.5 Aspects and assessment scale

The Standard Evaluation Protocol 2015-2021 required the Evaluation Committee to assess three main aspects of the institute and its research. These are (as described in the SEP):

1. *Research quality.* The committee assesses the quality of the institute's research and the contribution that research makes to the body of scientific knowledge. The committee also assesses the scale of the institute's research results (scientific publications, instruments and infrastructure developed by the institute, and other contributions to science).
2. *Relevance to society.* The committee assesses the quality, scale and relevance of contributions targeting specific economic, social or cultural target groups, of advisory reports for policy, of contributions to public debates, and so on. The point is to assess contributions in areas that the institute has itself designated as target areas.

3. *Viability.* The committee assesses the strategy that the institute intends to pursue in the years ahead and the extent to which it is capable of meeting its targets in research and society during this period. It also considers the governance and leadership skills of the institute's management.

These three main evaluation criteria were rated according to a four-category scale, as specified in the SEP. The judgement was given in qualitative form, though a quantitative figure could be added. The scale is as follows: 1. World leading/excellent; 2. Very good; 3. Good; 4. Unsatisfactory (see Annex 4).

The Evaluation Committee considered three additional topics. These are:

1. *PhD programmes.* The Evaluation Committee considered the supervision and instruction of PhD candidates.

2. *Research integrity.* The Evaluation Committee considered the institute's policy on research integrity and the way in which violations of such integrity are prevented.

3. *Diversity*. The Evaluation Committee considered the diversity of the institute. It is precisely the presence of mutual differences that can act as a powerful incentive for creativity and talent development in a diverse institute.

These topics were considered in qualitative terms (instead of using the four-category scale).

In addition to the topics above NWO formulated three generic questions for all NWO institutes, these are:

1. What is the institute's added value in the national context and its international position?

2. How does the institute stimulate and facilitate knowledge utilization and open access?

3. How does the institute structure, size and financial policy contribute to its mission?

# 2 Institutional framework of ARCNL

## 2.1 Mission

The Advanced Research Center for Nanolithography (ARCNL) is a unique research Center in the Dutch research landscape. It is a public-private partnership between the Netherlands Organisation for Scientific Research (NWO), the University of Amsterdam (UvA), the Vrije Universiteit Amsterdam (VU) and the semiconductor equipment manufacturer ASML. ARCNL focuses on the fundamental physics and chemistry involved in current and future key technologies in nanolithography, primarily for the semiconductor industry.

ARCNL has the ambition to be a worldwide leading research Center with a clear focus on fundamental research in the context of nanolithography technology. Next to a birth site for new knowledge and innovations, ARCNL wants to establish itself as a teaching and training site for a new breed of motivated scientists and technicians with an inclination towards applicable fundamental science. ARCNL has its own (temporary) laboratory and office buildings, located on the Amsterdam Science Park (ASP). Permanent facilities are currently under construction (Matrix VII building, ASP), expected to be realized in autumn of 2018.

*Nanolithography and EUV*

Lithography is a 'photographic' technique in the semiconductor industry using light to define the microscopic structures that make up integrated electronic devices. The field of nanolithography is concerned with creating ever-smaller structures, down to the nanometer (one millionth of a millimeter) range. To move towards such smaller structures, light of shorter wavelengths is required: replacing the typical, deep ultraviolet (DUV, 193 nm) light by light with a wavelength in the extreme ultraviolet range (EUV, 13.5 nm and below). This step has forced the semiconductor industry to develop radically novel technologies. The working principle of the latest EUV lithography instrumentation is based on a spectacular combination of phenomena, rooted in diverse fields of active research, such as laser physics and advanced optics, atomic and plasma physics, fluid dynamics and surface science. The point has been reached that significant progress in this new technology can no longer be maintained solely on the basis of further engineering. Instead, serious advances are required in fundamental knowledge in each of these areas of research. Generating precisely this basis of fundamental knowledge forms the key objective of ARCNL.

## 2.2 History

The initiative for ARCNL came from ASML in early 2013, when the company invited a total of four consortia to formulate plans for a joint research Center in the area of nanolithography. After a short bidding procedure, ASML selected the bid from Amsterdam, in which FOM institute AMOLF (now AMOLF) joined forces with University of Amsterdam (UvA) and Vrije Universiteit Amsterdam (VU), with solid support from the Foundation for Fundamental Research on Matter (FOM, now NWO-I). As ARCNL's founding partners, UvA, VU, NWO and ASML have committed themselves to support ARCNL for a minimum duration of 10 years, starting in January 2014.

## 2.3 Research

ARCNL's research programme is presently composed of 12 research groups. Each group is headed by one or more group leaders. These are full or associate professors appointed by

one of the two Amsterdam universities and assistant professors on a tenure track within NWO. The group leaders supervise compact teams of PhD students and postdocs, in most cases with the technical support of a group technician.

Here, we briefly describe the 9 groups that ARCNL had at the end of 2016 in the chronological order in which they were added to ARCNL's research programme.

### 2.3.1 Nanolayers Group

This group started in June 2014 and studies surfaces, interfaces, and very thin films on the atomic scale. The knowledge it generates is relevant for the delicate optics and other essential components of modern lithography machines.

### 2.3.2 Nanophotochemistry Group

This group started in June 2014 and focuses on the effects of the interaction between EUV light and the photosensitive films used in lithography, called 'photoresists'. This is a largely unknown territory.

### 2.3.3 EUV Plasma Processes Group

This group started in July 2014 and uses an extensive diagnostic toolset to characterize EUV light-emitting plasma at the atomic and molecular level.

### 2.3.4 EUV Generation and Imaging Group

This group started in July 2014 and aims to obtain a fundamental understanding of the physical processes occurring in laser-produced plasmas and to control the emission of radiation and particles. It also explores the possibilities of using EUV light for a new type of ultrahigh-resolution microscopy.

### 2.3.5 EUV Targets Group

This group started in September 2014 and uses ultrafast lasers and spectroscopy to study at every possible timescale the interaction between high-intensity laser light and metals passing through the four phases of matter: solid, liquid, gas and plasma.

### 2.3.6 EUV Photoemission Group

This joint group of ARCNL and AMOLF started in August 2015 and uses photoelectron spectroscopy – detecting electrons knocked out of a material by incoming photons – to study structural and chemical properties of surfaces and thin films, including molecular properties of EUV photoresist materials. Formally, this research group falls within the AMOLF-ARCNL Group.

### 2.3.7 EUV Photoresists Group

This group started in February 2016 and studies the chemical changes that occur within a wide range of photosensitive materials in response to incident EUV light. The aim is to gain fundamental understanding in order to design and synthesize new classes of materials with superior properties for nanopatterning.

### 2.3.8 EUV Plasma Modelling Group

This group started in July 2016 and uses a blend of theoretical and computational methods to understand and predict the formation and evolution of laser-produced tin plasmas with applications in EUV radiation generation.

### 2.3.9 AMOLF-ARCNL Group

This joint group of ARCNL and AMOLF started in August 2016.

## 2.4 Organisational structure

The 9 research groups that existed at the end of 2016 have been added with 3 additional groups (under construction). These 12 groups are organised into four major themes, "SOURCE", "METROLOGY", "SCANNER", "PROCESSES" plus a category labelled "EXTRA".

In the table below, you see an overview of groups per theme.

*Table 1. Groups per theme*

| **SOURCE** | **METROLOGY** | **SCANNER** | **PROCESSES** | **EXTRA** |
|---|---|---|---|---|
| EUV Plasma processes | EUV Generation & imaging | Nanolayers | EUV Photoelectron Spectroscopy | AMOLF-ARCNL Group |
| EUV Plasma Modelling | EUV Targets | Contact dynam-ics (NEW) | Nanophotochemistry | Accelerator-based EUV |
| | | | EUV Photoresists | |
| HHG generation of EUV (divided over the four themes) | | | | |

Organisational and contractual preparations led to a flexible and highly effective framework for this new type of public-private partnership that we now refer to as “the ARC-model” (see below). A cooperation agreement between the founding partners was signed in March 2014, detailing how the governance, finance and handling of intellectual property are arranged. A rapid start was made possible by launching ARCNL as a department within AMOLF. ARCNL became independent after reaching approximately 50% of its target size (50 fte) in September 2015. ARCNL remains lean and flexible by sharing its technical and administrative support staff with AMOLF. This is formally laid down in a support agreement.

*The 'ARC-model'*

The first 'invention' that has been made in the context of ARCNL is the organizational structure of ARCNL itself. This has been laid down in the ARCNL Cooperation Agreement and ARCNL loosely refers to it as the 'ARC-model', where ARC stands for Advanced Research Center. ARCNL associates four major characteristics with this model.

- An ARC is more than a project or a programme. It has a long-term perspective of at least ten years, which requires a solid financial and intellectual commitment of its founding partners.
- The financial contributions from the founding partners of an ARC add up to 50% for the private partners and 50% for the public partners. This ensures a balance between fundamental science on the one hand and on application-oriented research on the other.
- The financial contributions that the founding partners make to the ARC are substantial. This enables the ARC to follow its own course, independent of what might be fashionable in science and therefore more likely to generate external funding. Nevertheless, external funding forms an important instrument for the ARC to benchmark the Center and its staff with respect to other research institutions and for collaborations with external parties.
- An ARC is physically concentrated in a single location, rather than distributed over two or more locations. In this way, a genuine community is formed in which the combination of common goals and complementary expertise naturally leads to collaborative research.

As shown in Figure 1 below, the organizational structure of ARCNL is as follows.

- The research Center is headed by a Director, Prof. dr. Joost Frenken, who is supported by a Manager of Operations, Dr. Marjan Fretz.
- A Governing Board (GB) is in place, in which the four founding partners are represented. The GB keeps a close watch on ARCNL's course and establishes the formal link to the partner organizations.
- An independent Scientific Advisory Committee (SAC) monitors ARCNL's strategy and progress. It is made up of international experts on ARCNL's research subjects. Presently, the SAC is chaired by Prof. Marc Vrakking (Director Max Born Institute, Berlin). Over the period of 2014 - 2016, the ARCNL SAC convened two times, in January 2015 and January 2016.

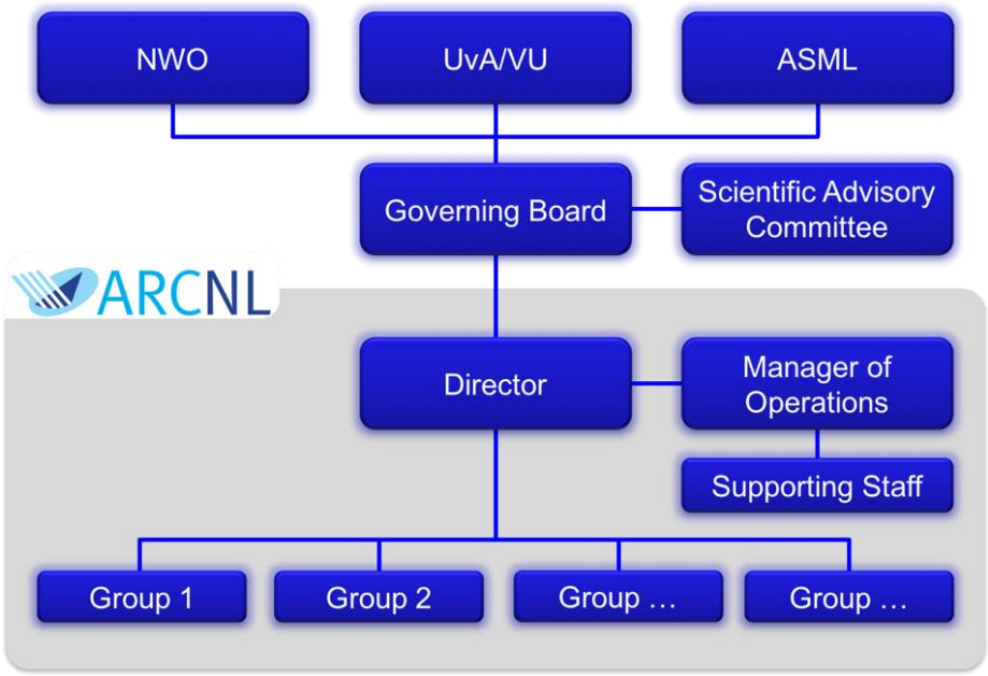


*Figure 1. Organisational structure of ARCNL*

## 2.5 Financial matters

ARCNL receives funding from four sources: (1) a base budget from the ARCNL partners, (2) a start-up subsidy from the City of Amsterdam and the Province of North-Holland, (3) a so-called TKI-supplement (see below), and (4) external project and program funding, acquired through research proposals.

The base budget from the partners amounts to M€ 7 annually, of which 50% comes from ASML and 50% from the public partners (NWO 32%; UvA 9%; VU 9%). The year 2016 was the first 'steady-state' year, in which ARCNL received full funding from all partners. The first two years, 2014 and 2015, were start-up years during which a reduced budget was received according to a start-up scheme, as agreed upon in the Cooperation Agreement.

The total budget for ARCNL for the period 2014 – 2023[##] is estimated to be M€ 100. The total exploitation costs are estimated at M€ 95; they are covered by the combination of the base budget from the partners, the TKI supplement and external grants. The City of Amsterdam and the Province of North-Holland awarded a start-up subsidy to ARCNL of in total M€ 5 (M€ 4,5 from Amsterdam and M€ 0,5 from North-Holland). This subsidy has been used to realize the temporary laboratory and office buildings and to purchase scientific equipment.

The TKI supplement is a 25% financial support fund offered by the Ministry of Economic Affairs through the *Topconsortium voor Kennis en Innovatie* (top-level consortium for knowledge and innovation) 'High Tech Systems and Materials' (TKI-HTSM), to match the private cash contributions in public-private partnerships. For ARCNL, this supplementing mechanism applies to the full contribution from ASML to the base budget of ARCNL. TKI support has to be applied for on an annual basis, based on separate, collaborative public-private research proposals.

[##] We refer here to a period that also includes the year 2023, thus covering the full 10-year minimum guaranteed lifespan of ARCNL.

In addition to the above-mentioned income, ARCNL researchers acquire external project and program grants from funding agencies, such as NWO and the EU (Horizon 2020). ARCNL researchers have been successful in obtaining prestigious personal grants such as ERC Starting and Advanced Grants and NWO Veni, Vidi, Vici grants. The total earning capacity of ARCNL's senior staff is estimated to increase to a steady-state level of 2,5 M€ / year in 2020.

**ARCNL financing structure**

| | 2014 | | 2015 | | 2016 | |
|---|---|---|---|---|---|---|
| | FTE* | % | FTE | % | FTE | % |
| **ARCNL** | | | | | | |
| *Funding*** | | | | | | |
| Direct funding | 6.4 | 84% | 25.1 | 76% | 37.2 | 81% |
| Research grants | 0 | 0% | 5.8 | 18% | 6.7 | 14% |
| Other | 1.2 | 16% | 2.0 | 6% | 2.2 | 5% |
| **Total funding** | **7.6** | **100%** | **32.9** | **100%** | **46.0** | **100%** |
| | | | | | | |
| *Expenditure* | **k€** | % | **k€** | % | **k€** | % |
| Personnel cost* | 1.347 | 63% | 3.127 | 53% | 4.238 | 52% |
| Other cost | 780 | 37% | 2.787 | 47% | 3.334 | 44% |
| **Total expenditure** | **2.127** | **100%** | **5.914** | **100%** | **7.572** | **100%** |

*** FTEs AMOLF support not included*

**Including support AMOLF and costs for advisors*

*2014: support AMOLF 380 keuro and advisors 200 keuro*

*2015: support AMOLF 770 keuro*

*2016: support AMOLF 913 keuro*

## 2.6 Staff

This section describes the composition of the 9 research groups that ARCNL had at the end of 2016 in the chronological order in which they were added to ARCNL's research program.

- Nanolayers Group
  *Start date:* June 2014
  *Group leader:* Prof. dr. Joost W.M. Frenken (1.0 fte)
  *Research area:* This group studies surfaces, interfaces, and very thin films on the atomic scale. The knowledge it generates is relevant for the delicate optics and other essential components of modern lithography machines.

| *Research staff – Nanolayers (fte)* | | | |
|---|---|---|---|
| | *2014* | *2015* | *2016* |
| *Group leader* | *0.75* | *1.0* | *1.0* |
| *PhD** | *1.5* | *2.9* | *3.0* |
| *Postdoc* | *0,3* | *1.8* | *1.3* |
| *Research technician* | *0.1* | *1.0* | *1.0* |

| | | | |
|---|---|---|---|
| *Guest* | *0.1* | *0.5* | *0.5* |

* *One PhD student came along to ARCNL with the group leader. This PhD student had started his project in 2012 at Leiden University*

- Nanophotochemistry Group
  *Start date:* June 2014
  *Group leader:* Prof. dr. A.M. (Fred) Brouwer (0.4 fte)
  *Research area:* This group focuses on the effects of the interaction between EUV light and the photosensitive films used in lithography, called 'photoresists'. This is a largely unknown territory.

| *Research staff – Nanophotochemistry (fte)* | | | |
|---|---|---|---|
| | *2014* | *2015* | *2016* |
| *Group leader* | *0.2* | *0.4* | *0.4* |
| *PhD* | *0.4* | *1.3* | *3.0* |
| *Postdoc* | *0* | *1.0* | *1.5* |
| *Research technician* | *0* | *0.8* | *1.0* |

- EUV Plasma Processes Group
  *Start date:* July 2014
  *Group leaders:* Dr. Oscar O. Versolato (1.0 fte; tenure track, since October 2015)
  Prof. dr. Wim Ubachs (0.3 fte)
  Prof. dr. Ronnie Hoekstra (0.3 fte)
  *Research area:* This group uses an extensive diagnostic toolset to characterize EUV light-emitting plasma at the atomic and molecular level.

| *Research staff – EUV Plasma Processes (fte)* | | | |
|---|---|---|---|
| | *2014* | *2015* | *2016* |
| *Group leader* | *0.4* | *0.9* | *1.6* |
| *PhD* | *0.3* | *2.5* | *4.7* |
| *Postdoc* | *0.3* | *1.2* | *0.6* |
| *Research technician* | *0.2* | *0.9* | *0.9* |

- EUV Generation and Imaging Group
  *Start date:* July 2014
  Group leaders: Dr. Stefan Witte (1.0 fte, tenured since September 2016)
  Prof. dr. Kjeld Eikema (0.3 fte)
  *Research area:* This group aims to obtain a fundamental understanding of the physical processes occurring in laser-produced plasmas and to control the emission of radiation and particles. It also explores the possibilities of using EUV light for a new type of ultra-high-resolution microscope.

| *Research staff – EUV Generation and Imaging (fte)* | | | |
|---|---|---|---|
| | *2014* | *2015* | *2016* |

| | | | |
|---|---|---|---|
| *Group leader* | *0.7* | *1.3* | *1.3* |
| *PhD* | *0.0* | *2.5* | *6.6* |
| *Postdoc* | *0.1* | *1.5* | *2.2* |
| *Research technician* | *0.0* | *0.8* | *1.0* |

- EUV Targets Group
  *Start date:* September 2014
  *Group leader:* Prof. dr. Paul Planken (1.0 fte)
  *Research area:* This group uses ultrafast lasers and spectroscopy to study at every possible timescale the interaction between high-intensity laser light and metals passing through the four phases of matter: solid, liquid, gas and plasma.

| *Research staff – EUV Targets (fte)* | | | |
|---|---|---|---|
| | *2014* | *2015* | *2016* |
| *Group leader* | *0.5* | *1.0* | *1.0* |
| *PhD* | *0.3* | *2.2* | *3.0* |
| *Postdoc* | *0.0* | *1.2* | *1.0* |
| *Research technician* | *0.0* | *1.0* | *1.0* |

- EUV Photoemission Group
  *Start date:* August 2015
  *Group leader: (past)* Dr. Niklas Ottosson (tenure track from August 2015 until February 2017). Currently, recruitment in progress for new tenure tracker.
  *Research area:* This joint group of ARCNL and AMOLF uses photoelectron spectroscopy – detecting electrons knocked out of a material by incoming photons – to study structural and chemical properties of surfaces and thin films, including molecular properties of EUV photoresist materials. Formally, this research group falls within the AMOLF-ARCNL Group (see last item in this list).

| *Research staff – EUV Photoemission (fte)* | | | |
|---|---|---|---|
| | *2014* | *2015* | *2016* |
| *Group leader* | *0.0* | *0.6* | *1.0* |
| *PhD* | *0.0* | *0.0* | *1.3* |
| *Postdoc* | *0.0* | *0.0* | *0.0* |
| *Research technician* | *0.0* | *0.2* | *1.0* |

- EUV Photoresists Group
  *Start date*: February 2016
  *Group leader:* Dr. Sonia Castellanos (1.0 fte, tenure track)
  *Research area:* This group studies the chemical changes that occur within a wide range of photosensitive materials in response to incident EUV light. The aim is to gain fundamental understanding in order to design and synthesize new classes of materials with superior properties for nanopatterning.

| *Research staff – EUV Photoresist (fte)* |
|---|

| | *2014* | *2015* | *2016* |
|---|---|---|---|
| *Group leader* | *0.0* | *0.0* | *0.9* |
| *PhD* | *0.0* | *0.0* | *0.5* |
| *Postdoc* | *0.0* | *0.0* | *0.0* |
| *Research technician* | *0.0* | *0.0* | *0.0* |

- EUV Plasma Modelling Group
  *Start date*: July 2016
  *Group leader:* Dr. Jan van Dijk (0.2 fte)
  *Research area:* This group uses a blend of theoretical and computational methods to understand and predict the formation and evolution of laser-produced tin plasmas with applications in EUV radiation generation.

| *Research staff – EUV Plasma Modelling (fte)* | | | |
|---|---|---|---|
| | *2014* | *2015* | *2016* |
| *Group leader* | *0.0* | *0.0* | *0.1* |
| *PhD* | *0.0* | *0.0* | *0.0* |
| *Postdoc* | *0.0* | *0.0* | *0.0* |
| *Research technician* | *0.0* | *0.0* | *0.0* |

- AMOLF-ARCNL Group
  *Start date*: August 2016
  *Coordinator:* Prof. dr. Huib Bakker
  *Research Area:* Next to the EUV Photoemission Group, this joint group of ARCNL and AMOLF contains typically three PhD projects in three different AMOLF research groups, in close collaboration with research groups within ARCNL. At the end of 2016, two PhD students started their projects in this group. The third project started in early 2017.

This table shows the status of number of FTEs employed on date mentioned

| | 1 Jan 2014 | | 31 Dec 2014 | | 31 Dec 2015 | | 31 Dec 2016 | |
|---|---|---|---|---|---|---|---|---|
| | # | fte | # | fte | # | fte | # | fte |
| **Research staff** | | | | | | | | |
| group leaders | 1 | 0.5 | 7 | 4.3 | 9 | 6.3 | 11 | 7.5 |
| postdocs | 0 | 0 | 3 | 3 | 7 | 7 | 8 | 8 |
| PhD students | 0 | 0 | 7 | 7 | 19 | 17.7 | 28 | 26.7 |
| research technicians | 0 | 0 | 2 | 1.9 | 6 | 5.9 | 6 | 5.9 |
| **Total research staff** | **1** | **0.5** | **19** | **16.2** | **41** | **36.9** | **53** | **48.1** |
| **Other staff** | | | | | | | | |
| Support staff ARCNL | **0** | 0 | 3 | 3 | 5 | 4 | 4 | 3.5 |
| Support staff AMOLF* | 0 | 0 | 10 | 9 | 14 | 13 | 17 | 16.2 |
| Visiting fellows | 0 | 0 | 0 | 0 | 5 | 4.5 | 8.0 | 7.2 |
| **Total staff** | **1** | **0.5** | **32** | **28.1** | **65.0** | **58.4** | **82.0** | **75.0** |

** From 2014 onwards, additional support personnel were hired by AMOLF to provide ARCNL with technical and administrative support.*

# 3 Assessment of the institute ARCNL

## 3.1 Strategy and targets ARCNL

ARCNL represents a bold undertaking in private-public partnerships. The Center was initiated through a vision from ASML, and the initiative of established academic scientists in recognizing the potential to bring the cutting-edge outputs of fundamental science into innovative approaches to applied questions. The focus is on the frontier of nanolithography, which at present is represented by the challenges of using extreme ultraviolet (EUV) light sources for patterning.

The proposals on which the Center was established, and which have served to shape its rapid early development draw on themes of using advanced laser, plasma and spectroscopic approaches, and the application of atomic/molecular understanding to create new pathways in EUV lithography. The specific topics include formation and characterization of plasma sources, metrological challenges, materials innovations for optics and alignment, and the chemical physics of EUV interaction with resists. The approaches to these topics are intended to be deeply informed by approaches now underway at ASML, to develop enabling understanding for existing approaches and to explore new approaches that are outside of ASML's current work and/or too early stage or high risk for ASML to address directly.

The Center involves close partnerships and stakeholder engagement from the key industrial partnership with ASML, the NWO and neighbouring organization AMOLF, and from the Universities (UvA and VU). These organizations have provided substantive monetary and organizational support making it possible for the Center to rapidly develop its own totally new infrastructure for its unique mission.

## 3.2 Research themes

The Center has shaped its program around four research themes: EUV sources, metrology at all stages of EUV nanolithography, the development of new materials for optics and alignment, and the challenges of EUV resists. These are addressed individually in the sections below, along with the additional topic of the integration of AMOLF and ARCNL activities. The numerical metrics of the Center are summarized in the Table below. The demonstration of a growing publication productivity in 2017 is as expected for a young Center that has spent its first years establishing its research infrastructure and training entering graduate students who are just now reaching their potential as young researchers.

The committee wishes to note that it was provided with limited information and what is tabulated below is what could be deduced from what was received or accessed by the committee from follow-on questions and interactions. We (the committee) would highly recommend that ARCNL maintain and be able to routinely provide such information (and more, see section 4) at high level of timeliness and accuracy.

*Table 2. Numerical metrics*

| **Output between 2014-September of 2017** | | | |
|---|---|---|---|
| | 2015 | 2016 | 2017 |
| Papers published/ accepted | | 3 | 9 |

| | | | |
|---|---|---|---|
| Papers submitted | | | 2 |
| IDF's written | 25<br>(total between 2014-2017); of which 12 were filed as new patent applications) | | |
| IDF's under review | 2 | | |
| Patent applications | At least 12 | | |
| Invited talks | At least 46 | | |
| Other | | | |

The committee notes, that (apparently from the ASML side) there has been some emphasis on the metrics in the Table above as 'key performance indicators.' The committee wishes to emphasize that a) ARCNL is still developing its infrastructure and its relationship with ASML, and there needs to be a longer-term view in assessing progress, and b) the use of numerical metrics, while providing some indications, can only complement deep expert assessment of the scientific outcomes that constitute the true delivery of societal value from ARCNL.

### *3.2.1 Research theme 1: Sources*

**Research goals and context**

Ever since the early days of EUV lithography in the 90's, the source has been identified the most challenging component of the EUV lithography machine. Originally, several source technologies competed but the last decade or so, the liquid-jet or liquid-droplet laser plasma has been the concept of choice for HVM. Tin was identified early as a suitable target material for 13.5 nm due to its spectral overlap with MoSi multilayer mirrors. The key industrial issues in source development have been and still are in-band power, debris mitigation, and up-time.

Overall the tin-droplet laser-plasma source is a very complex system involving a wide range of scientific as well as engineering disciplines, from laser physics and hydrodynamics over plasmas, atomic physics, and spectroscopy, to debris production, mitigation, and chemistry. Although many of the individual fields are mature and since long significant fields in science, it is unusual to have them all in the same system interacting at the same time. Thus, the source is a complex and novel "organism" suitable for basic scientific investigations. Such deeper scientific understanding of the inner workings of the organism can certainly contribute to improved industrial source performance. Equally important is the opposite – the source provides access to a new parameter space that may open up new windows for high-quality science, also outside the prime EUV focus of the group. Thus, it is a good topic for ARCNL, both for its basic science scope and for its stakeholders' interest.

**Status of ARCNL activity**

The panel was impressed by the progress of the group led by Dr. O Versolato (including Prof. dr. Wim Ubachs and Prof. dr. Ronnie Hoekstra).

In a short time they have built an advanced and versatile experimental arrangement with impressive diagnostic capabilities as well as a well-functioning group of dedicated graduate students. One of the major achievements is the study of the mechanical interaction of an intense laser pulse and a tin droplet. Beautiful and revealing shadow pictures of the time evolution of a tin droplet after the impact of one or several laser pulses have been taken.

The unique droplet high-speed imaging system impressed us and should become an important tool when investigating different laser pulse time sequences for maximum conversion efficiency. As for publications, the group reports 4 published papers plus 7 in preparation as well many invited (11) and contributed talks (12). Given the early stage, this is excellent record. Finally, the interaction with the large efforts on the source at ASML/Cymer appear to develop positively for both ARCNL and ASML.

**Potential for the future**

As for the future, the panel endorses the continued collaboration with the laser team of dr. Witte et al. on the development of lasers with large parameter space. Together with the diagnostic capabilities discussed above, these lasers will allow detailed investigations of different modes of laser-plasma excitations and, hopefully, optimization of plasma temperature, debris emission and conversion efficiency.

Although the panel gives the source group full support both for its previous efforts and its directions for the future, we have one item of concern and one topic of strategic importance. The item of concern is the present lack of advanced plasma modelling. Since the departure of dr. Van Dijk it appears as there is no one that can model the system in house. The laser plasma is a very complex system and it is extremely difficult to interpret experiments correctly without a good model. Thus, good modelling at an appropriate level of detail is an integrated part of good experiments and experimenters and modellers need to interact. The panel strongly recommends that ARNCL seeks to build a long-term stable plasma modelling activity with strong connection to the experiments.

The topic of strategic importance concerns the source technology on the long term. The panel would like to see some effort going into alternative source concepts, or at least into the thinking of alternative source concepts. The droplet-target laser plasma is already 27 years old and it would be wise to revisit the case to see if there is anything new on the horizon. Also within the droplet-target concept, it would be wise to think about the choice of tin, which was an early semi-business/semi-technical decision based on the MoSi mirror reflectivity curve. Tin is messy and it might be worth taking a new look for optimizing the whole system, optics AND source, in light of progress the last 20 years. In short, we recommend ARNCL source work to add some resources for developing blue-sky high-risk-high-reward projects and encourage its staff to think and spend time on such an idea making process.

In the neighbouring Thematic Area “Metrology”, the group of Prof. dr.Paul Planken investigates ideas of structuring of the tin target, claiming potential for increased absorption of the laser light and, thus, increased CE. The panel is not convinced this subject would be its first priority for increasing CE since it only affects the first picoseconds of the several tens of nanoseconds long laser-plasma interaction. If this effort is continued it should be strongly coupled to laser-plasma modelling of the full temporal length.

### *3.2.2 Research theme 2: Metrology*

**Research goals and context**

The EUV generation and imaging group studies and optimizes the generation of EUV light from a laser-driven plasma source. The group is in the process of building a table-top broadband EUV source by means of higher-harmonic generation. The group also studies EUV-based methods for surface and three-dimensional imaging, structure analysis and imaging through opaque layers (collaboration with Prof. dr. Paul Planken's group).

Once the group and the institute as a whole have been fully developed, it is intended to be a unique science-oriented research Center for nanolithography with focus on the EUV-based optical version of it.

**Status of ARCNL activities**

The EUV Generation and Imaging group comprises approximately 12 fte and has accomplished a surprisingly quick start at ARCNL, helped by the vicinity of the Laser Laboratory of the VU and the strong background of the two group leaders (dr. Witte & Prof. dr. Eikema) in laser and imaging research. At this moment, three years after the very start of the institute, the quantified number of "key performance indicators" (KPI's per year) has not been realized. What can be observed from the numbers is a quick ramp-up of the number of KPI's. For instance, the number of publications in 2017 of the EUVGI-group will be close to 10 and shows a sharp increase with the number of 2 for the year 2016.

A large number of subjects in the research domain of the group are being pursued and remarkable results have already been accomplished in the past 2.5 years of existence of the group. We mention among others:

- a versatile laser source for plasma generation with a flexible tailoring of the time-dependent light amplitude within a single pulse (sub-pulse creation, ramp function). It is the opinion that this flexible laser source is a very important tool for studying laser-driven plasma generation.

- a variety of EUV-source analysis and imaging methods has been developed. Unconventional approaches are the retrieval of a complex object-field distribution with the aid of the diffracted far-field intensity data and the application of a spectrally broadband Hartmann test to the characterization of EUV sources. An impressive accomplishment is the imaging of for instance grating markers through optically opaque wafer layers. This work is done in Planken's group and the Witte-Eikema group offers assistance to this important research topic with immediate relevance for sponsor ASML.

- the design of the compact broadband EUV source based on higher-harmonic generation has been finalized and the first components arrive by the end of 2017. Important in this respect is the hiring of a tenure-track group leader for this subject.

The demonstration of the various research topics pursued in this group during the lab tour showed the great skills of this group and the important role they are likely to play in the ARCNL institute. It was impressive to see what experimental set-ups and capabilities have been installed in the laboratories in the relatively short time since the founding of the institute. The panel is confident that this group will produce (further) excellent research results in the future.

Fruitful interaction with stakeholder ASML in general and the research group of ASML-Cymer in particular is going on and will expand in the future. An interesting example of a direct interaction with ASML is the detection of the position of alignment marks by means of high-frequency, optically induced acoustic waves propagating in an optically opaque process layer (see also Prof. dr. Planken's group).

**Potential for the future**

The availability in the near future of a compact and broadband EUV source will enable the group to focus on research for next-generation lithography, for instance in the 6 nm window. By means of this shorter-wavelength EUV source the group in particular and the institute in general can timely identify certain existing roadblocks on this track to higher resolution and work on solutions to remove these. The group follows a promising track with respect to the

detection of hidden defects in EUV-masks or EUV-multilayers. The reliable and fast at-wavelength detection of defects is extremely important for the success of EUV-lithography.

### 3.2.3 Research theme 3: Scanner

**Research goals and context**

The research goals are based on fundamental studies of Interface & thin film formation in the context of the needs of EUV lithography. Interfaces and atomically thin films are and will even become more essential in lithography technology. Although mirrors based on multilayers are being realized and in production and surface stress measurement is not needed anymore, the atomic-level understanding of the deposition process may become very important when/if going to 6 nm EUV litho, requiring new mirror materials. The study of interfaces under radiation still is a timely subject.

**Status of ARCNL Activities**

Some of the early research focused on the development of the methodology to study the growth of molybdenum on silicon in real time at very high resolution. This is scientifically high-quality research, however, the problems the group is pursuing with this work are outdated. Deposition and grain formation during Ru deposition is excellent. Unfortunately, the equipment is very fault-sensitive. This hampers the scientific output to some extent.

Fortunately, new areas of research are being developed and the committee is optimistic that there is the potential for this group to deliver on its potential through focus on the areas outlined below:

EUV-transparent materials The research on transparent materials is excellent work. Also, here the sensitivity of the equipment, in terms of fragile, plays a role in the output so far. The work on graphene may not be of interest of ASML, the work on monolayers should be.

Effects of EUV-photons The equipment is still under construction, yet this could lead to very interesting research outcomes on exposure of surfaces by high-energy light, water molecules, hydrogen radicals and tin contamination

Friction and adhesion Studying the friction (force) at an atomic scale (nanotribology) as well as theory as in experiments is excellent and has great potential. The approach of taking nanostructures into account to influence (super)lubrication and especially the use of diamond like carbon (or graphene) could be a successful direction and is expected to gain very useful information.

Contact Dynamics Although just started, the visualisation of true contact areas of wafers, and in addition different coatings as studied and proposed in the other groups, gives beautiful insight in the field of adhesion and friction. The idea to apply new strategies to make friction switchable is challenging and exciting.

**Potential for the future**

Overall, the research capability is of high quality, especially taking into account the short time that the institute is running and taking into account the complex and fragile equipment. New research ideas that are initiated show the potential of the group. On the other hand, one has to consider research subject that are, although interesting for basic research, not of interest (anymore) for the customer.

The team leader Prof. dr. Frenken, has faced serious demands on his time as the director of ARCNL. As recommended in section 4, providing sufficient staff support to allow Prof. dr.

Frenken to delegate more of his management responsibilities will be essential to the development of this research area.

### 3.2.4 Research theme 4: Processes

**Research goals and context**

The overarching goals of this theme are to (a) develop new EUV resist materials; (b) develop better understanding of the mechanisms by which resists are exposed; and (c) ultimately, develop future resists that will give good performance in Resolution, Sensitivity and Line-edge-roughness (RLS) by gaining solutions to the stochastic issues related to EUV light.

The ARCNL Processes theme focuses on the synthesis and characterization of new EUV resist materials, and sophisticated techniques for studying the physics and chemical mechanisms of their exposure.

**Status of ARCNL activities**

This processes research area is new and understaffed.

The nanophotochemistry group leader, Prof. dr. Fred Brouwer, is an expert in the photochemistry of materials spanning organic and inorganic molecules, radical ions, and molecular machines. He participates at ARCNL at 0.4 fte. His group has synthesized tin-oxo clusters from literature methods and has characterized these resists using interference lithography, and by exposure to UV light followed by evaluation using FTIR and XPS lithography. Additionally, Prof. Brouwer and his group are developing/utilizing several resist characterization techniques. These techniques include pump-probe spectroscopy, low energy electron spectroscopy, and optical density measurements. Specifically, the pump-probe spectroscopy is being develop at ARCNL and is designed to provide the most important, yet elusive, information about the physics and chemistry of EUV exposure—details about the short-lived photoelectrons. He is the senior professor and team leader in this group, but his part-time status may have limited his impact on the group.

Prof. dr. Fred Brouwer is a well-established professor with expertise in photochemistry, with a significant fraction of his time spent working at ARCNL. However, his publication rate within ARCNL is limited, and the young research group he leads is facing serious stresses in its development.

Dr. Sonia Castellanos is a tenure-track assistant professor who joined ARCNL 1.5 years ago. She is an expert in the syntheses of metal oxide and metal-organometallic frameworks. Her group has esynthesized 3-4 novel platforms of metal oxide molecules or self-assembled metal-oxide films.

Dr. Sonia Castellanos is a promising young researcher, but her two graduate students have been with her for less than a year. She is on a rapid growth curve to become a strong researcher, but will need a few more years before she can establish a track-record of publications, and before she can develop a reputation within the international lithography and photoresist community.

Former theme leader Dr. Niklas Ottosson had a very promising start to his career at ARCNL, had defined research interests that were very important part of the Processes Theme, and well-appreciated by ASML. However, Dr. Niklas Ottosson decided to leave ARCNL for personal reasons, and he has left a large hole in the capabilities of this theme. The position for the group leader of the EUV photoelectron spectroscopy group remains unfilled.

Overall, this panel believes that the research done by the groups in the Processes Theme is currently good, and is on a trajectory to become very good with the potential for an international reputation provided (a) dr. Sonia Castellanos continues to grow in her role as a group leader, and can establish a productive relationship with ASML, (b) a strong candidate can be found to become a group leader on the EUV Photoemissions group, and (c) Prof. Fred Brouwer's research group demonstrates a growth in the capabilities of his unique resist evaluation instrumentation and the number of publications.

**Potential for the future**

Recommendations for future growth are:

1. Supporting Dr. Castellanos' continued growth is key to the success of the Processes technology effort. She needs to focus on a few important objectives:

    a. She should focus as much as possible on developing her own unique metal-containing EUV photoresists. The panel recommends putting aside some of the advanced characterization techniques for a while, so that she can focus instead on multiple quick loops of synthesis followed by rapid characterisation of contrast curve and imaging performance with time at PSI. She should write ASML IDF's on the new materials that she develops.
    b. Dr. Sonia Castellanos should seek out opportunities to get engage with (a) at the two Amsterdam Universities, (b) at ASML and within the international EUV resist community. The panel suggests that she creates courses for masters or PhD students in metal-oxide chemistry or photoresists. She should be supported in developing deeper engagement with ASML through seminars at ASML on her research, or teaching a short course at ASML on EUV metal resists. She should present her research at two international conferences each year.
    c. Once the position is filled for the group-leader of the Photoemissions group, Dr. Sonia Castellanos should then switch her focus back from using the powerful characterization techniques available at beamlines around Europe and to those unique capabilities being developed at ARCNL.

2. Hiring a replacement for Dr. Niklas Ottosson is critical to the growth and success of the Processes Research Theme.

3. Prof.Brouwer's leadership should support the growth of the Processes Theme in at least three key ways:

    a. Helping Dr. Sonia Castellanos reach her full potential, by mentoring her and helping her become better known at the two Amsterdam universities and within his photochemical community.
    b. Prioritizing recruitment and hiring of a replacement for Dr. Niklas Ottosson.
    c. Delivering ASML-relevant results from his time-resolved pump-probe spectroscopy. This approach has the potential to dramatically increase the world's understanding of the EUV exposure mechanism. This work has the potential to increase the world's recognition of ARCNL, and open the door to significant research funding.

### *3.2.5 Research theme extra: ARCNL-AMOLF integration*

The scientific staff members are engaged with the activities at ASML, some deeply and productively while others are still developing relationships with ASML. The vision for ARCNL as it matures is for the understanding that the faculty develop through interaction with ASML to inform their approaches to developing substantive new ideas with real potential for impact.

The goal of the ARCNL-AMOLF integration area is to expand the pool of faculty, and thus the range of scientific opportunities to inform new approaches to advance EUV lithography.

To accomplish this, ARCNL includes a competitive proposal process in which faculty from AMOLF propose topics of research related to EUV nanolithography, for a time-limited (typically 4 years) period of funding. The first round of such projects has begun in the past year, with three projects established as collaborations among AMOLF-ARCNL faculty. The three topics are: the time resolved (fs) measurements of the response of metals under IR laser irradiation, instrumentation development and demonstration of sub-wavelength imaging, and the use of quantum dots as a potential future photoresist.

**Potential for the future**

These projects are, as they ought to be, high-risk and high potential. In addition to the potential outcomes they provide an opportunity to explore new areas without a permanent commitment, to expand the experimental infrastructure of ARCNL, and to create a broader community of faculty engaged with the deep expertise of ASML personnel. These projects are in the early stages of development, and rigorous assessment of their engagement with ASML, technical, instrumentation, and knowledge development impacts should be an integral part of their on-going management.

## 3.3 Research quality

In assessing the overall research quality of the Center, the panel believes it is important to recognize the youth of the organization and its trajectory for the future. In this context, the panel is in some sense rating the Center on its potential for future achievement based on what has been accomplished in its first three years.

a. A key factor in the potential for long-term success is the originality and impact of the research areas under investigation. The Center's focus is on the underpinning physical and chemical processes in all stages of deep EUV lithography. This focus is developing more rapidly in some research areas than others, and where it is working well it is delivering innovative new research topics observed publications and invention disclosures, many of which are unique to this Center.

b. Another major factor the panel has considered in assessing progress is the development of state-of-the-art research instrumentation and early demonstration of its performance and utility. There have been impressive results in this area particularly in the Sources and Metrology areas, with growing publication output validating the quality of the outcomes.

c. A third factor recognizes the importance in this Center of the connection to the challenges of industrial nanolithography. In some sense, ARCNL is creating a new way of working – not as a purely fundamental or purely applied research Center, but as a new approach that draws on both fundamental and applied research approaches to create new directions. As metrics of progress, we consider invention disclosures, uptake of ARCNL discoveries into ASML, and the influence of industrial expertise in creating new lines of academic inquiry. The panel observes good early progress in these metrics.

d. Additional factors include the development of human capabilities, diversity, and information management. Although the report outline has placed in a different category than Research Quality, the panel feels that these are important to research quality. As discussed in those sections of the report, given its early stage of development the Center is doing very well in these areas.

Based on the progress during the first few years of Center's development, and the potential trajectory, the panel concludes that given its early stage of development this Center is performing very well, and has the potential to grow to excellent status by the time of its next review. Despite our concerns about numerical summaries, we would award a ranking of '2' for Research Quality to represent the discussion points above.

## 3.4 Relevance to society

The new approach to public private partnerships that is envisioned and developing at ARCNL will in itself be a major potential benefit to society. The Netherlands has a very strong and effective basic research infrastructure. However, as is also the case around the world, the translation of the forefront results of this basic research into economic and other societal benefits often occurs by a slow diffusion process enabled by graduate students and post-docs who move to the private sector. The vision for ARCNL is to allow the most powerful new research outcomes to be brought directly into contact with an area of industrial innovation (EUV lithography) where they are likely to create new directions and previously unexpected progress. This represents a mode of operation that is neither basic nor applied research as traditionally defined, but instead may be considered the apex of a triangle, for which the other vertices are fundamental and applied. In establishing ARCNL, basic research topics that have high potential for such impact have been identified in the context of a strong pull for the advances that could accrue. Successfully achieving this approach to research impact requires an effective engagement with both the fundamental research structure and the commercial innovation and development process. Each has its own culture and norms, and ARCNL must effectively bridge them. This is not easy, but it is doable, and success in this task will create an example that can be more easily be followed in the future, allowing significant acceleration of the pace at which societal investment in basic research yields positive impacts.

In addition to the institutional model, ARCNL is also training young scientists to work effectively in bridging fundamental science and innovative impact. Specifically:

- ARCNL educates and trains young scientists in a scientific environment with an open view on technological applications. Having finished their education at ARCNL they are very well qualified to consider either a further career in academia or in a high-technological environment such as ASML.

- During their teaching and education period at ARCNL graduates will have translated innovative ideas into invention disclosures and then patent applications. If these ideas are granted the patent status, they will strengthen the international patent position of a country like the Netherlands and Europe in general, thus providing job opportunities and economic prosperity. The development of new technical outcomes from the research in ARCNL, such as better EUV resists, can make a huge economic impact on the Dutch economy because of their importance to ASML and because their development will enable the economic manufacture of faster integrated circuits at a reasonable cost.

The panel considers the approach that ARCNL is developing to connect fundamental research approaches to advanced commercial technologies is of itself crucially relevant to society. Societal needs to derive economic benefits and new capabilities from fundamental research, must be addressed more rapidly and more effectively, and this new model has the potential to do so.

In addition, the specific research focus of the Center, delivering the next stages of lithography at the scale of 13.5 nm and below in the future, has extremely large economic

significance. This arises both in the market for chips fabricated with high density, and in the impact the enhanced capabilities have on delivering more services to society.

Because these points are so compelling, and because this Center has a unique potential to deliver these values, the panel assessed a numerical ranking of 1 for Relevance to Society.

## 3.5 Viability

As noted above, ARCNL represents a bold undertaking in private public partnerships. The Center was initiated through a vision from ASML, and the initiative of established academic scientists in recognizing the potential to bring the cutting-edge outputs of fundamental science into innovative approaches to applied problems.

This new model for public-private partnership is exciting, but there are significant stresses in managing the effort of building the Center while also sustaining the vision of its unique role as a bridge of innovation. Some of these stresses come from the University partners who face financial pressures due to their engagement with ARCNL. Some stresses may come from sister institution AMOLF where it will take time and effort to develop mutual understanding of how the purely fundamental focus at AMOLF can work effectively with the mission inspired fundamental focus of ARCNL. Other stresses may come from the industrial partner, ASML, where the accelerated time frame of industrial practice (including rapid changes in focus) can create impatience that overshadows the significant positive interactions that are already developing, and the potential for longer term strategic benefits (including hedge against technical surprise).

After three years in operation, ARCNL management and teams need to focus on delivering the success that the early investment in developing the Center is making possible. There is still much work to be done in completing the ambitious plans for cutting edge instrumentation, and recruiting and nurturing the young faculty who will bring the Center to its full strength. The viability of the Center depends on meeting these challenges, and the committee strongly feels that all the stakeholders must confront the stresses outlined in the previous paragraph and work to resolve them in ways that allow the Center management to focus on fully developing the Center according to its strategic plan during the next several years.

ARCNL has made excellent progress in establishing its management, laboratory space, research infrastructure, and launching research activities. In doing so it has been generously supported by ASML, its University partners, AMOLF and NWO. ARCNL's strategic plan lays out its vision for connecting fundamental research to the problems of nanolithography, and the specific research directions that will deliver that vision.

However, there are concerns for its viability based on the complexity of its interaction with multiple partners who have different expectations for their investment in ARCNL. This tension arises at the University side, where faculty time and other resources are being committed to ARCNL, at the AMOLF side where the focus is on curiosity-driven (rather than mission inspired) fundamental research, and at the ASML side due to the quick pace of industrial work and priorities. The panel's recommendations in section 4 include some inputs on this topic. For the ranking of the Center, we note that we do consider this tension to be a threat to the Center's viability which needs to be addressed. The ARCNL leadership has recognized these issues and is carrying out a ‘blueprint’ process for mitigating the risks. The evaluation committee believes that the ARCNL leadership needs to be provided significant support from NWO in engaging all of their stakeholders in this process.

Because of the balance of excellent beginnings, and risks due to stakeholder expectations, the panel assessed a numerical rating of 2 for Viability.

## 3.6 Considerations regarding organisation, management policies and staffing

### *3.6.1 PhD programmes*

The PhD students are very positive about the institute: as well as scientific content, support, supervision as well as working atmosphere.

Because the PhD-students have different employers (VU, UVA, NWO), their training and scientific developing plans are different. Some take part in a graduate school (VU) some have excess to different courses (NWO). Some have obligations in giving lectures, others not. Although, this is not problematic for the PhD, as they told us, it is something to be taken into account for the near future when the number of students will increase.

The daily (or weekly) guidance of the student within a research group is experienced as very positive. The mutual interaction with other groups should be more intensified. The poster sessions that being organised since a few months is a good example to improve this.

The interaction with ASML for graduate students is very limited to our impression. Some students have visited ASML's labs, but direct graduate student interaction with ASML staff on a research basis seems limited. Also, apparently there is dominantly one-way direction from staff of Veldhoven to Amsterdam, which could be easily be modified in visits to ASML by the students. This would benefit those PhD students interested in careers in industry instead of academia.

### *3.6.2 Research integrity policy*

All graduate students get (different) classes on research integrity when they join ARCNL; this is still diverse based on with which institution (NWO, VU UvA) the student is affiliated.

Post-docs joining ARCNL are likely to have had integrity training in their graduate work, but this should be reinforced and standardized with an ARCNL short-course on integrity issues for all incoming post-docs or other research staff.

ARCNL has worked with AMOLF on a detailed data management plan, and implementation plans for sharing and using data are in place. As this moves into effect, standard training for all incoming students, post-docs and other research staff should be established.

### *3.6.3 Diversity*

The Center's research staff includes a range of nationalities and races due to the fact that a lot of staff, especially among students and postdocs, come from abroad. Representation of women is limited, with best statistics among graduate students where it is about 23%.

The Center works with the WISE and GENERA programmes to help in attracting more women. There are some support structures for women, such as mentoring programs, but the committee was not offered any documentation of their effectiveness.

The Center should establish some results-based metrics of success. There should be ongoing assessment of the Center's diversity, with a baseline goal of at least meeting the same diversity statistics in the recruitment pool. The Center should also take action in one area where it does have direct control, which is in the outcomes for the women and under-represented minorities among its graduate students and post-docs. Are they engaged with the most interesting projects? Do they publish, give talks, and move on to good positions at a

high rate? Are they given training opportunities to develop skills in negotiation, communication in group setting, etc. that are traditionally difficult areas for members of underrepresented groups? The committee recommends that such goals be established and included as success criteria for the Center's next review.

## 3.7 Supplementary questions by the NWO Executive Board

### *3.7.1 Generic questions*

- What is the institute's added value in the national context and its international position?

The institute has a unique role in stimulating innovation by bridging cutting-edge fundamental science into commercial impact with an industrial partner. The Center's specific focus on the fundamental issues in accomplishing commercially viable nanolithography with EUV sources is uniquely suited to have international impact because one of the world's leading industrial firms in this area, ASML, is an active partner in the Center.

- How does the institute stimulate and facilitate knowledge utilization and open access?

The Center is committed to open publication and has an excellent plan for open data management. Its unique contribution is in providing a communication pathway between the fundamental research community and the real needs of rapidly advancing commercial innovation (in this case in the area of EUV nanolithography). Fundamental scientists who wish to have a practical impact from their work are often hindered by not having a realistic understanding of the practical needs. The strategic mission of ARCNL includes bridging this gap.

- How does the institute structure, size and financial policy contribute to its mission?

As a very young institution, ARCNL's structure and size were specifically proposed to meet its mission of fundamental science, in connection with commercial applications. Its structure includes a significant breadth of topics that cover all aspects of EUV nano-lithography. This ambitious structure has progressed more rapidly in some areas than others, and bringing all areas into full operation is an immediate challenge for the next few years of the Center. The financial policy of the Center includes a core base of cash contributions jointly provided by ASML and NWO, with additional in kind contributions from the other stakeholders. The committee feels that constructive engagement with the other stakeholders (although a smaller fraction of the finances) is essential to the long term health and success of the Center. In addition, as discussed in section 4, the committee sees evidence that the Center may need more support staff to address administrative issues, record keeping, general issues in graduate and post-doctoral training, and free the research faculty as much as possible for emphasis on delivering technical results.

# 4 Conclusions and recommendations

## 4.1 Conclusions

As noted in the previous section, the committee views the establishment of ARCNL as an important new approach to public-private partnership in the Netherlands and believes that the Center has a very good chance of success that will deliver highly significant outcomes. The Panel is impressed by what has been established, at this early stage, by ARCNL in terms of the laboratory set up and equipment, as well as in terms of personnel development. The institute has been able to attract top (senior) scientists from UvA, VU, AMOLF and other great institutions in the Netherland, and young high potential from all over the world.

However, while what has been accomplished is very good, progress has (not unexpectedly in the early days of a new institution) been uneven, and there are stresses in terms of burdens on the scientific staff, and interactions between ARCNL and its partner institutions. The Center will need several more years of focused effort to bring all its research areas up to their full potential, fully realize the mutual benefits of its working relationship with ASML, and have fully established all the aspects of its physical, support and operations infrastructure.

The committee believes that the time frame required is consistent with the plan for the Center. Completing the Center's early progress and achieving the projected outcomes on this time scale will be an outstanding accomplishment.

## 4.2 Recommendations

The committee has formulated recommendations that are intended to provide guidance in the continuing effort needed for ARCNL's high potential for achieving world class research, technical impact and broader societal benefits. The background for these recommendations is presented in Section 3.

The committee has formulated two over-arching recommendations:

1. ARCNL must be allowed to focus over the next several years on completing the growth of its research teams and their activities, and making its operational processes sustainable. Expectations from its partners and stakeholders must take this into account. In particular:

    a. The Center needs to stabilize its present activities and its key operational relationship with ASML, before being pushed to raise more external funding.
    b. The Center needs to operate without micro-management to address urgent needs of its stakeholders. The Center's Governing Board must prioritize the long term goal of building a Center for excellent fundamental research at the public-private interface.
    c. The Center's academic partners must recognize that ARCNL is developing a new approach, different from both traditional curiosity-driven basic research, and traditional pathway-driven work in applied research. ARCNL faculty must be motivated and assessed accordingly.
    d. The committee believes that NWO must play a role in adjudicating stakeholder expectations, and in doing so must be sensitive to the special needs of a strong industrial engagement (in this case with ASML). Some approaches to ensure the necessary long-term perspective may include: minimum 3-year perspective in each project decision

or review report, maximum annual reviews of the project, Director's funding, and general trust building among the stakeholders

2. ARCNL must develop a sustainable operational structure as it moves past its early development in which many parallel requirements have had to be addressed rapidly. In doing so, management must allocate sufficient budget for non-research staff to support administrative, record keeping, educational, communication and other outreach activities of the Center. The committee believes that the Center may be understaffed in this way at present, and that addressing this issue is one key to insuring the long term health of the Center. Key indicators that should be evaluated in this regard:

    a. The ability to present a strong evidence-based technical case for the accomplishments of the Center. This was woefully missing in the material that was provided in advance to this evaluation committee[1]. Provision of high quality technical information on work accomplished should be major point of assessment in the next review of ARCNL.
    b. Development of standard approaches, designed to free research staff from having to create and maintain their own processes, for record keeping, support of students and post-docs, communication of research results, and all other overhead that accompanies a large Center.

### 4.2.1 *Specific recommendations*

The committee developed many specific recommendations during its assessment, most of which are embedded in the text of Section 3. These are extracted here for ease of review.

a. We (the committee) highly recommends that ARCNL maintain and be able to routinely provide information such as that partially tabulated in the Table Numerical Metrics in section 3 at a high level of timeliness and accuracy.
b. With regard to numerical metrics, the committee wishes to emphasize that a) ARCNL is still developing its infrastructure and its relationship with ASML, and there needs to be a longer term view in assessing progress, and b) the use of numerical metrics, while providing some indications, can only complement deep expert assessment of the scientific outcomes that constitute the true delivery of societal value from ARCNL.
c. The panel strongly recommends that ARNCL seeks to build a long-term stable plasma modelling activity with strong connection to the experiments.
d. We recommend ARNCL source work to add some resources for developing blue-sky high-risk-high-reward projects and encourage its staff to think and spend time on such an idea making process.
e. The panel is not convinced structuring the tin target would be its first priority for increasing CE. If this effort is continued it should be strongly coupled to laser-plasma modelling of the full temporal length.
f. In the scanner area, a focus on 'next-generation' EUV lithography should be developed.

[1]The material that was provided in advance to the evaluation committee was massive and repetitive, and covered administrative, procedural and strategic content. However there was virtually no information provided about the actual work that has been completed since the Center was established. The failure to provide such information reflects poorly on NWO in setting requirements for the pre-read material and on ARCNL in selecting what material to present. This problem undermined the evaluation committee's review, because as members were scrambling during the meeting to identify what has been accomplished rather than being able (as one would normally expect to do in such a review) to focus on synthesis and analysis of overall information about the Center.

g. In the scanner theme, providing sufficient staff support to allow Prof. dr. Frenken to delegate more of his management responsibilities will be essential to the development of this research theme.
h. For the Processes Theme, the growth of young faculty should be actively supported, and the position of group-leader of the Photoemissions group must be filled very soon.
i. For the Processes Theme, improved relationship with ASML, and delivering ASML-relevant results from the time-resolved pump-probe spectroscopy must be priorities.
j. For the AMOLF-ARCNL joint projects, rigorous assessment of their engagement with ASML, technical, development of instrumentation, and knowledge development impacts should be an integral part of their on-going management.
k. The Center will need to oversee and align the different educational processes that graduate students affiliated with NWO, UvA and VU encounter.
l. Senior level graduate students should be given more opportunity to engage with ASML.
m. ARCNL should establish a short course on research integrity for incoming post-docs to establish a standard base of understanding and attention to these issues.
n. As the data management plan moves into effect, standard training for all incoming students, post-docs and other research staff should be established.
o. The Center should establish some results-based metrics of success in diversity with a baseline goal of at least meeting the same diversity statistics in the recruitment pool.
p. The Center should actively develop methods to support positive outcomes for the women and under-represented minorities among its graduate students and post-docs.

## 4.3 Ranking: executive summary

In the following, we repeat our summary statements for each of the three topical headers requested by NWO. We again emphasize that the valuation panel felt uneasy giving numerical ratings based on the criteria listed in Section 1 of the report. The main reason for this is that ARCNL was only established three years ago, which means that they are still in the build-up phase of an institution. The panel felt that rating them on criteria that clearly are intended for mature institutions is not really feasible. The panel discussed providing very strong explanations concerning the context of the youth of ARCNL along with their ratings, but still were very concerned that numerical ratings could be taken out of context with unintended consequences. The committee therefore wishes to emphasize that all of our rankings are provided in the context of the youth of ARCNL and its potential to excel in each of the three categories.

### *4.3.1 Research quality*

In assessing the overall research quality of the Center, the panel believes it is important to recognize the youth of the organization and its trajectory for the future. In this context, the panel is rating the Center on its potential for future achievement based on what has been accomplished in its first three years.

- A key factor in the potential for long-term success is the originality and impact of the research areas under investigation. The Center's focus is on the underpinning physical and chemical processes in all stages of deep EUV lithography. This focus is developing more rapidly in some research areas than others, and where it is working well it is delivering innovative new research topics observed publications and invention disclosures, many of which are unique to this Center.

- Another major factor the panel has considered in assessing progress is the development of state-of-the-art research instrumentation and early demonstration of its performance

and utility. There have been impressive results in this area particularly in the Sources and Metrology areas, with growing publication output validating the quality of the outcomes.

- A third factor recognizes the importance in this Center of the connection to the challenges of industrial nanolithography. In some sense, ARCNL is creating a new way of working – not as a purely fundamental or purely applied research Center, but as a new approach that draws on both fundamental and applied research approaches to create new directions. As metrics of progress, we consider invention disclosures, uptake of ARCNL discoveries into ASML, and the influence of industrial expertise in creating new lines of academic inquiry. The panel observes good early progress in these metrics.
- Additional factors include the development of human capabilities, diversity, and information management. Although the report outline has placed in a different category than Research Quality, the panel feels that these are important to research quality. As discussed in those sections of the report, the Center is doing well in these areas.

Given the progress at this early point of the Center's development, and the potential trajectory, the panel concludes that this Center is performing well, and has the potential to grow to excellent status by the time of its next review. Despite our concerns about numerical summaries, we would award a ranking of '2' for Research Quality to represent the discussion points above.

### *4.3.2 Relevance to society*

The panel considers the approach that ARCNL is developing to connect fundamental research approaches to advanced commercial technologies is of itself crucially relevant to society. Societal needs to derive economic benefits and new capabilities from fundamental research, must be addressed more rapidly and more effectively, and this new model has the potential to do so.

In addition, the specific research focus of the Center, delivering the next stages of lithography at the scale of 13.5 nm and below in the future, has extremely large economic significance. This arises both in the market for chips fabricated with high density, and in the impact the enhanced capabilities have on delivering more services to society.

Because these points are so compelling, and because this Center has a unique potential to deliver these values, the panel assessed a numerical ranking of 1 for Relevance to Society

### *4.3.3 Viability*

ARCNL has made excellent progress in establishing its management, laboratory space, research infrastructure, and launching research activities. In doing so it has been generously supported by ASML, its University partners, AMOLF and NWO. ARCNL's strategic plan lays out its vision for connecting fundamental research to the problems of nanolithography, and the specific research directions that will deliver that vision.

However, there are concerns for its viability based on the complexity of its interaction with multiple partners who have different expectations for their investment in ARCNL. This tension arises at the University side, where faculty time and other resources are being committed to ARCNL, at the AMOLF side where the focus is on curiosity-driven (rather than mission inspired) fundamental research, and at the ASML side due to the quick pace of industrial work and priorities. The panel's recommendations above include some inputs on this topic. For the ranking of the Center, we note that we do consider this tension to be a threat to the Center's viability which needs to be addressed. The ARCNL leadership has recognized these issues

and is carrying out a ‘blueprint’ process for mitigating the risks. The evaluation committee believes that the ARCNL leadership needs to be provided significant support from NWO in engaging all of their stakeholders in this process.

Because of the balance of excellent beginnings, and risks due to stakeholder expectations, the panel assessed a numerical rating of 2 for Viability.

# Annex 1. Curricula Vitae of Evaluation Committee Members

**Ellen D. Williams – Chair**

Ellen Williams is a Distinguished University Professor at the University of Maryland, where she is working at the interface of energy technology and policy. Before returning to the University in January of 2017, she was the Director of the Advanced Research Projects Agency, ARPA-E, in the Department of Energy. The Advanced Research Projects Agency-Energy (ARPA-E) advances high-potential, high-impact energy technologies that are too early for private-sector investment.

Prior to Senate confirmation for her role in ARPA-E, Dr. Williams had been the Chief Scientist at BP (2010-2014), and a Distinguished University Professor in the Institute of Physical Science and Technology and the Department of Physics at the University of Maryland. At Maryland she founded and led the University's Materials Research Science and Engineering Center from 1996 through 2009.

Dr. Williams has a distinguished history of professional service, including chairing the development of the NAS report on Technical Issues for the Comprehensive Test Ban Treaty, and extensive work in providing technical advice to the U.S. government, primarily through the Departments of Energy and Defence. She is a member of the National Academy of Sciences, a foreign member of the Royal Society (London), a fellow of the American Physical Society, American Vacuum Society and American Academy of Arts and Sciences, and has been recognized by awards from the American Physical Society and the Materials Research Society.

**Robert Brainard**

Robert Brainard received his B.S. in Chemistry from U.C. Berkeley in 1979. He synthesized and studied the reaction mechanisms of organoplatinum compounds during his graduate studies with Professor George Whitesides at MIT and Harvard University. After receiving his Ph.D. in 1985, he studied the reaction mechanisms on copper and silver surfaces under ultrahigh vacuum conditions as a post-doctoral student in Professor Robert Madix's laboratory at Stanford University.

Robert worked for Polaroid 1987-1990, where he developed new gold and sulfur chemistry for use in the chemical sensitization of silver halide photographic emulsions. He worked at Shipley/Rohm & Haas 1990-2005, where he did product development research in the areas of: electrodeposited, dielectric, color filter, DUV, EUV, X-ray and e-beam photoresists.

Robert is now a tenured Professor at the College of Nanoscale Science and Engineering within the SUNY Polytechnic, in Albany NY investigating new materials for use in EUV lithography and biological applications. His specific research interests include:

- EUV photoresist exposure mechanisms
- High quantum efficiency EUV photoresists
- Design and synthesis of photoacid generators
- Chemistry of polymer thin films
- Acid amplifiers for use in EUV Lithography
- Design and synthesis of photoimagable hydrogels for cell growth
- Molecular Organometallic Resists for EUV (MORE)

**Hans Hertz**

Hans Hertz received his Ph.D. in optical physics 1988 at Lund University, Sweden, and did his post-doc at Dept. of Applied Physics, Stanford University. Since 1997 he is professor of Biomedical Physics at the Royal Inst. of Technol. (KTH), Stockholm. At KTH he leads an ~30 person cross-disciplinary research group with focus on x-ray science and technology, but also including optics and acoustics.

He pioneered the liquid-jet/droplet laser-plasma source, the metal-jet electron-impact source as well as laboratory x-ray microscopy, and the research has resulted in a few spin-off companies. Present research interests include high-resolution phase-contrast x-ray imaging, x-ray fluorescence imaging, x-ray microscopy, x-ray sources and x-ray optics, always with biomedical applications in mind. 2006-12 he was the first head of the Department of Applied Physics, spring 2013 he was visiting professor at Dept. of Radiology, Stanford University and fall 2014 he was a fellow at Stellenbosch Inst. of Advanced Studies, South Africa.

He is presently chairman of the Board of the MAX IV Laboratory (Lund) and Excillum AB (Stockholm). He is a fellow of the Royal Academy of Sciences (KVA), the Royal Swedish Academy of Engineering Sciences (IVA), and Royal Physiographical Society. He has published >150 scientific papers, holds >25 patents, has several invited talks/year, and has advised >25 PhD's.

**Dave Blank**

Prof. dr. ing. Dave Blank is Distinguish Professor as well as Chief Scientific Ambassador at the University of Twente. He received his PhD in Physics in 1991 from the University of Twente, Netherlands for his dissertation on High-Tc thin films prepared by laser ablation. Prof. Blank continued to work at the University of Twente in different professorships in Applied physics and material science. In 1998 he worked as a visiting scientist at the Laboratory of Advance Materials at Stanford University.

From 2007 – 2015 he was Scientific Director of MESA+ Institute for Nanotechnology and currently Chairman of the Executive Board of NanoNext NL, a national programme on nanotechnology, member of the Advisory Council for Science, Technology and Innovation Policy (AWTI) of the Dutch government and parliament and he is appointed as Captain of Science in the Top team High Tech Systems and Materials of the Department of Economic Affairs, with focus on intensifying the mutual exchange between science and industry.

He is leading the route on quantum- and nanotech of the Dutch Science Agenda on societal challenges. Among many honorary memberships and awards, he received the Royal decoration of Knighthood of the Order of the Dutch Lion in 2010 and a VICI laureate of the Dutch Science Foundation for his work on artificial materials for nanoscale devices. He is the co-founder of three start-up companies on deposition equipment and related thin film applications.”

**Joseph Braat**

Joseph Braat studied physics at Delft University of Technology. After his graduation he joined the coherent optics group of professor Serge Lowenthal at the Institut d'Optique, Orsay/France (thesis on holography using spatially incoherent light). From 1973 to 1998 he worked at Philips Research, Eindhoven. He has participated in the early research on optical disc systems, in particular the diffraction of light by the information carrying structure, the conception of read-out methods and the design of light paths for optical disc systems. Simultaneously he got interested in optical lens and system design and in optical lithography.

In 1988 he was appointed as a part-time professor of geometrical optics at Delft University, in 1998 as the full professor of optics (faculty of Applied Physics). Research topics were EUV-lithography, optical aperture synthesis for astronomy, high-density optical recording and optical long-distance metrology. Joseph Braat is the author or co-author of some 200 scientific publications and has been attributed 60 US patents.

# Annex 2. Programme of the Site Visit 20-22 September 2017

**Wednesday 20 September 2017**

Arrival Panel members and transport to Hotel V Fitzeaustraat (Fitzeaustraat 2, Amsterdam)

16:45 – 18:00 Panel meeting (open) and official installation by member NWO Board (RvB)
18:00 – 19:30 Dinner (Restaurant The Lobby – Hotel V Fitzeaustraat)
19:30 – 21:30 Closed Panel session (further introduction, division of roles and working method)

**Thursday 21 September 2017**

08:30 – 08:45 Transport from Hotel V Fitzeaustraat to ARCNL
09:00 – 09:15 Welcome at ARCNL
09:15 – 10:00 Introduction by Director, followed by interview with Director and Manager of Operations
10:00 – 10:30 1 x presentation + discussion scientific group: EUV targets group
10:30 – 10:45 Coffee break
10:45 – 12:15 3 x presentations + discussion scientific groups (30 min each) (e.g., EUV Plasma Processes group, EUV Generation and Imaging group, Nanolayers group)
12:15 – 13:15 Lunch (informal; PhD students, postdocs and technicians invited)
13:15 – 14:45 3 x presentations + discussion scientific groups (30 min each) (e.g. EUV Photoresist and Nanophotochemistry, AMOLF-ARCNL group)
14:45 – 15:00 Coffee break
15:00 – 16:30 Lab tour
16:30 – 17:15 Interview with Chair Scientific Advisory Committee ARCNL
17:15 – 17:45 Closure, closed Panel session
17:45 – 18:00 Transport from ARCNL to hotel or direct to restaurant
19:00 – 19:15 Transport from Hotel V Fitzeaustraat to Restaurant Merkelbach
19:15 – 22:00 Dinner & closed session at Restaurant Merkelbach
22:00 – 22:15 Transport from Restaurant Merkelbach to Hotel V Fitzeaustraat

**Friday 22 September 2017**

07.30 – 08:30 Optional: closed breakfast session
08:30 – 08:45 Transport from Hotel V Fitzeaustraat to ARCNL
09:00 – 10:00 Interview with Director, Manager of Operations and complete scientific staff –focus on future plans and new 'Blueprint' ARCNL
10:00 – 10:15 Coffee break
10:15 – 11:00 Interview with Governing Board/stakeholders
11:00 – 11:45 Interview with PhD-students (selected group)
11:45 – 12:15 Interview with Management Team on diversity and integrity

| | |
|---|---|
| 12:15 – 13:15 | Lunch with Director, Manager of Operations and group leaders |
| 13:15 – 17:00 | Closed Panel session: finalizing Panel Report |
| 17:00 – 17:30 | Presentation by Panel Chair to Director, Manager of Operations and scientific staff |
| 17:45 – 18:00 | Transport from ARCNL to Hotel V Fitzeaustraat |
| 19:30 – 19:45 | Transport from Hotel V Fitzeaustraat to Restaurant Jacobsz |
| 19:45 – 22:00 | Dinner at Restaurant Jacobsz, together with Director, Manager of Operations and complete scientific staff |
| 22:00 – 22:15 | Transport from Restaurant Jacobsz to Hotel V Fitzeaustraat |

# Annex 3. Quantitative data composition and financing

Table 1. Composition of ARCNL; research and support staff

The table shows the status of number of FTEs employed on date mentioned

| | 1 Jan 2014 | | 31 Dec 2014 | | 31 Dec 2015 | | 31 Dec 2016 | |
|---|---|---|---|---|---|---|---|---|
| | # | fte | # | fte | # | fte | # | fte |
| **Research staff** | | | | | | | | |
| group leaders | 1 | 0.5 | 7 | 4.3 | 9 | 6.3 | 11 | 7.5 |
| postdocs | 0 | 0 | 3 | 3 | 7 | 7 | 8 | 8 |
| PhD students | 0 | 0 | 7 | 7 | 19 | 17.7 | 28 | 26.7 |
| research technicians | 0 | 0 | 2 | 1.9 | 6 | 5.9 | 6 | 5.9 |
| **Total research staff** | **1** | **0.5** | **19** | **16.2** | **41** | **36.9** | **53** | **48.1** |
| **Other staff** | | | | | | | | |
| Support staff ARCNL | **0** | 0 | 3 | 3 | 5 | 4 | 4 | 3.5 |
| Support staff AMOLF* | 0 | 0 | 10 | 9 | 14 | 13 | 17 | 16.2 |
| Visiting fellows | 0 | 0 | 0 | 0 | 5 | 4.5 | 8.0 | 7.2 |
| **Total staff** | **1** | **0.5** | **32** | **28.1** | **65.0** | **58.4** | **82.0** | **75.0** |

* From 2014 onwards, additional support personnel is hired by AMOLF to provide ARCNL with technical and administrative support.

Table 2. ARCNL financing structure

| | 2014 | | 2015 | | 2016 | |
|---|---|---|---|---|---|---|
| | FTE* | % | FTE | % | FTE | % |
| **ARCNL** | | | | | | |
| *Funding*** | | | | | | |
| Direct funding | 6.4 | 84% | 25.1 | 76% | 37.2 | 81% |
| Research grants | 0 | 0% | 5.8 | 18% | 6.7 | 14% |
| Other | 1.2 | 16% | 2.0 | 6% | 2.2 | 5% |
| **Total funding** | **7.6** | **100%** | **32.9** | **100%** | **46.0** | **100%** |
| | | | | | | |
| *Expenditure* | **k€** | % | **k€** | % | **k€** | % |
| Personnel cost* | 1.347 | 63% | 3.127 | 53% | 4.238 | 52% |
| Other cost | 780 | 37% | 2.787 | 47% | 3.334 | 44% |
| **Total expenditure** | **2.127** | **100%** | **5.914** | **100%** | **7.572** | **100%** |

** FTEs AMOLF support not included

*Including support AMOLF and costs for advisors

2014: support AMOLF 380 keuro and advisors 200 keuro

2015: support AMOLF 770 keuro

2016: support AMOLF 913 keuro

# Annex 4. Explanation of the categories

The committee assesses the institute on the three assessment criteria: research quality, relevance to society and viability. These criteria are assessed both in qualitative terms (with arguments) and quantitative terms (in one of the four categories, see the table below).

*Table 3. Meaning of categories in SEP 2015-2021*

| Category | Meaning | Research quality | Relevance to society | Viability |
|---|---|---|---|---|
| 1 | World leading / excellent | The institute has been shown to be one of the few most influential research groups in the world in its particular field. | The institute makes an outstanding contribution to society. | The institute is excellently equipped for the future. |
| 2 | Very good | The institute conducts very good, internationally recognised research. | The institute makes a very good contribution to society. | The institute is very well equipped for the future. |
| 3 | Good | The institute conducts good research. | The institute makes a good contribution to society. | The institute makes responsible strategic decisions and is therefore well equipped for the future. |
| 4 | Unsatisfactory | The institute does not achieve satisfactory results in its field. | The institute does not make a satisfactory contribution to society. | The institute is not adequately equipped for the future. |

In addition to the three criteria, every assessment also considers at least three further aspects: PhD programmes, research integrity, and diversity. These aspects are only assessed in qualitative terms.

# Annex 5. Terms of Reference

*The board of The Netherlands Organisation for Scientific Research (NWO) hereby issues the following Terms of Reference to the assessment committee of ARCNL, chaired by Prof.dr. Ellen Williams.*

| Topic | Description |
|---|---|
| Title | External evaluation of ARCNL of the period 2011 – 2016 |
| Why | NWO organizes periodic evaluations of each research institute within the organisation every six years. This is part of the standing agreement with the Ministry of Education, Culture and Science. Together with Royal Netherlands Academy of Arts and Sciences (KNAW) and the Association of Universities in the Netherlands (VSNU), NWO has stated to conduct these evaluations according to the Standard Evaluation Protocol (SEP).<br><br>The goal of the periodic assessments is primarily to identify the quality of the research and the societal relevance and secondly to - partly on the basis of the assessment results - determine the mission and the basic funding for the next six years (2018-2023). |

| | |
|---|---|
| What | The assessment committee evaluates quality and relevance to society of the research conducted by the institute as well as its strategic targets and the extent to which it is equipped to achieve them. The committee does this by judging the institute's performance on the three SEP assessment criteria, taking into account current international trends and developments in science and society in the analysis. Each criterion should receive a ranking in one of the four categories in accordance with the SEP guidelines. The committee also ensures that the qualitative assessment (text) and the quantitative assessment correspond. Furthermore, the committee should give recommendations for improvement.<br><br>The three SEP assessment criteria are:<br><br>- Research quality<br>- Relevance to society<br>- Viability<br>The assessment committee also gives a qualitative evaluation on three additional aspects:<br><br>- PhD programmes<br>- Research Integrity<br>- Diversity<br>Further information about the criteria and additional aspects can be found in chapter 2 of the Standard Evaluation Protocol (SEP).<br><br>In addition to the topics above NWO has formulated three questions:<br><br>1. What is the institute's added value in the national context and its international position?<br>2. How does the institute stimulate and facilitate knowledge utilization and open access?<br>3. How does the institute's structure, size and financial policy contribute to its mission? |
| For whom | - The researchers themselves in order to establish where they stand, how they can improve and what the research should aim for.<br>- The management of the institute who wishes to track the impact of their policy.<br>- The board of NWO who decides on the accountability of the institute and the support for the institute.<br>- Other stakeholders from, for example, the society and private sector.<br>- The Ministry of Education, Culture and Science has requested a portfolio analysis of all the research institutes of NWO and the Royal Netherlands Academy of Arts and Sciences in 2018. The results of the SEP-evaluations will act as input for this portfolio analysis. |
| Who | The independent assessment committee consists of 4-7 renowned international experts within the realm of the institute. Each committee member signs a statement of impartiality and confidentiality. |

| | |
|---|---|
| How | The assessment committee will be supported by a liaison officer from NWO and an independent secretary. The necessary documentation to conduct the assessment will be made available to the committee one or two months before the site visit. This documentation includes at least a self-evaluation by the institute, a strategy document of the institute and the conclusions and recommendations from the previous assessment. If feasible the institute may provide a bibliometric analysis or a different study of its own choice to support the self-evaluation. The assessment committee will be invited to the institute for a site visit of two days during which the institute will present itself in short lectures and interviews by the committee. The assessment committee will deliver a draft evaluation report to the NWO board no later than eight weeks after the site visit and a final version no later than 12 weeks after the site visit. Finally the NWO board will publish the assessment report on the website accompanied by a public statement. |
| When | The site visit will take place in September or October 2017. NWO distributes the necessary information and documents to the committee 1 or 2 months in advance of the site visit. For further information on the general time schedule please refer to the attached Standard Evaluation Protocol. |
| Contact | Daphne den Hollander MSc (Birch) and Dr. Michiel van den Hout (NWO) |

*Necessary documents that will be made available to the assessment committee:*

- Self-evaluation
- Strategy document
- Further description of what the committee needs to know about the scope/context, assessment questions, method, time schedule, final report
- Programme of the site visit
- Standard Evaluation Protocol (SEP)
- Conclusions and recommendations from previous evaluation
- Response NWO to the previous evaluation report
- <optional> Bibliometric analysis