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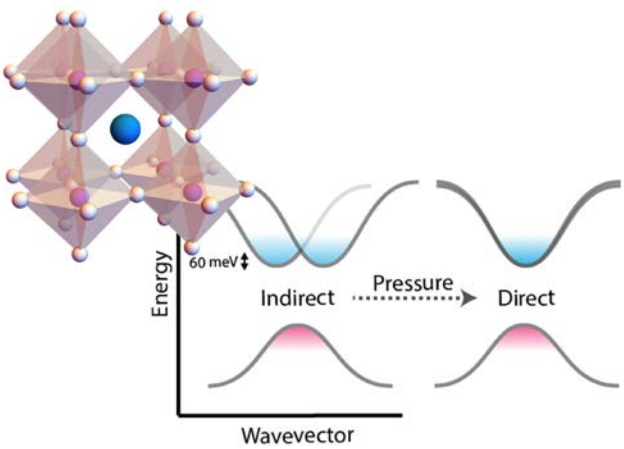
Annual report 2017

FOM programme nr. 131

Light management in new photovoltaic materials



Metal halide perovskite crystal structure, which leads to a slightly indirect bandgap by the Rashba effect. Under hydrostatic pressure, the bandgap becomes completely direct.
T. Wang, B. Daiber, J.M. Frost, S.A. Mann, E.C. Garnett, A. Walsh, and B. Ehrler, Energy. Env. Sci. **10**, 509 (2017)

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0. Introduction

The FOM/NWO Focus Group "Light Management in New Photovoltaic Materials" (LMPV) was established at AMOLF in 2012, as one of the strategic initiatives of FOM to strengthen research on renewable energy in the Netherlands. The goal of the LMPV program is to develop fundamental understanding of the interaction of light with photovoltaic nanomaterials, and apply this knowledge to -eventually- realize photovoltaic conversion concepts that surpass existing technology. The LMPV research program targets three long-term efficiency goals: (1) *towards 30% efficiency*: light coupling, trapping and carrier collection geometries to reach or stretch the ultimate limits of Si technology; (2) *30-40% efficiency*: hybrid solar cell geometries based on organic/inorganic materials, and thin-film/wafer-Si tandem cells; (3) *beyond 40% efficiency:* novel III-V nanowire geometries and other hybrid material combinations on the nanoscale. The program brings together expertise in fundamental nanophotonics, materials synthesis, device physics, spectroscopy, nanofabrication, and nanocharacterization.

Achieving the goals of the program requires synthesis and development of entirely new materials and solar cell architectures, and fundamental research on hybridizing strategies combining concepts from dielectrics and metamaterials, to managing light on length scales from the molecular scale to that of a solar panel, and to harness extreme materials properties to reach the efficiency limits governed by reciprocity and thermodynamics. The LMPV program's primary goal is to achieve fundamental understanding of basic physical phenomena that are relevant for future (>5-10 years) application in photovoltaics. In many cases, demonstrator devices are made as well, either at AMOLF or with external collaborators.

The LMPV Focus Group research is carried out under the supervision of three group leaders that were hired at AMOLF on a tenure-track position (Erik Garnett, Bruno Ehrler, Esther Alarcón Lladó) and the program leader, Albert Polman. In 2017, Erik Garnett received tenure at AMOLF and was appointed professor by special appointment at the UvA. Aside from the research at AMOLF, the LMPV program has funded two satellite PhD projects in the groups of Daniel Vanmaekelbergh (UU) and Ruud Schropp (later Adriana Creatore/Erwin Kessels) (TUE).

The LMPV Focus Group is funded by FOM/NWO (5.400 k€) and AMOLF (2.270 k€) for the period 2011-2019. The four research groups also acquire additional funds to expand their groups. So far 13.370 k€ was raised from projects funded by FOM, NWO, TKI, ERC, etc.. These external funds are an essential aspect of the LMPV program, and have enabled the program to grow to its present size of ~30 researchers (+ masters students). This report provides an overview of the achievements in 2017.

1. Scientific results 2017: highlights

Integrating sphere microscopy

(LMPV PhD student Sander Mann, group Garnett)
Nanoscale materials are promising for solar cells because their physical dimensions are on the order of the wavelength of light. This leads to a variety of complex optical phenomena that for instance enhance absorption and emission. However, quantifying the performance of these nanoscale devices frequently requires measuring absolute absorption at the nanoscale and, remarkably, there is no general method capable of doing so directly. We developed such a method based on an integrating sphere, but modified to achieve submicron spatial resolution. We explored the limits of this technique, by using it to measure spatial and spectral absorptance profiles on a wide variety of nanoscale systems, including different combinations of weakly and strongly absorbing and scattering nanomaterials (Si and GaAs nanowires, Au nanoparticles). This measurement technique provides quantitative information about local optical properties that are crucial for improving solar cells with nanoscale dimensions or nanoscale surface texturing.

Perovskite nanowire extrusion

(LMPV student Sebastian Oener, group Garnett)
Halide perovskite materials have shown the most rapid rise in solar cell performance ever recorded. Their solution-processability and low native surface recombination velocity make them particularly attractive for nanostructured solar cells. However, so far nanoscale patterning has been hampered by their dissolution in many common solvents used during lithography. We solved this problem taking inspiration from the extrusion

process, which is commonly used to form plastics into arbitrary shapes. We show that nanoporous anodic aluminum oxide templates can be used as the extrusion mask to make high-quality, single-crystalline halide perovskite nanowires with tunable length and diameter. We also show that by altering the extrusion mask, we can make halide perovskite nanomaterials with other cross-sectional profiles. The resulting materials show photoluminescence quantum yield up to ~29%, making them suitable for both fundamental nanophotonic studies and high-performance solar cells.

Highly transparent singlet fission solar cell with multistacked thin metal contacts for tandem solar cells

(LMPV postdoc Jumin Lee, group Ehrler)

Down-conversion of energy by singlet fission could allow to “upgrade” conventional silicon solar cells by doubling the number of electrons from high-energy photons. We have previously shown that using a parallel-connected tandem solar cell, the external quantum efficiency (photon-to-electron conversion) can be up to 106%, something that is impossible with any conventional solar cell. However, currently these parallel tandem solar cells are limited by the poor transmittance of the electrical contacts. We have now been able to fabricate solar cells that transmit more than 80% of below-bandgap photons, while maintaining more than half their current density. We further simulate that such transparent solar cells would dramatically improve the power conversion efficiency over the previous parallel tandem solar cells.

Indirect to direct bandgap transition in methylammonium lead halide perovskite

(LMPV PhD student Tianyi Wang, group Ehrler)

The efficiency of solar cells made from hybrid perovskites is now comparable to silicon, despite only a few years of development. One puzzle has been the surprisingly slow charge-carrier recombination in hybrid perovskites. We find evidence for a peculiar bandstructure that would allow for such slow recombination: the conduction band is split (in k-space) such that recombination needs phonon interaction. We find evidence for such splitting, termed “Rashba-splitting”, from the steady-state and time-resolved photoluminescence and absorption, and we find that the bandstructure becomes completely direct at high hydrostatic pressure (>325 MPa), i.e. the splitting vanishes. For highest solar cell efficiencies, a direct bandgap is desirable, and our result directs the design of hybrid perovskites to allow even higher voltage for solar cells.

Direct writing of metal nanowires in aqueous solutions with scanning probe microscopy

(LMPV PhD student Mark Aarts, group Alarcon Llado)

Direct writing has recently emerged as an alternative to lithography for the maskless patterning of metallic and semiconducting materials. In particular, direct-writing strategies based on electron-driven reactions have the potential to simultaneously address fundamental issues and technological challenges. We have developed a new strategy to fabricate metal nanostructures on demand based on electrochemical atomic force microscopy. We have explored the physico-chemical mechanisms behind the metal patterning and its limits, reaching structures with a size limited by the tip radius (~25nm). With the extension of this method to other materials, such as semiconductors and electronically conductive polymers, new limits can be set for designing extravagant PV device architectures with targeted photonic properties.

III-V nanowires on Si for tandem cells

(LMPV PhD student Nasim Tavakoli, group Alarcon Llado)

Semiconducting nanowires (NWs) have been recognized as promising materials for future high-performance solar cells. In particular, coupling of light into waveguided modes of vertical NWs result into absorption cross-sections >>100%. The spectral dependence of light in-coupling on the NW geometry provides new degrees of freedom in designing tandem solar cell structures. For instance, from a detailed balance analysis we show that for the GaAs/Si 2 terminal combination, the efficiency can be raised from 36.2% (thin GaAs on Si) to 38% (GaAs NWs on Si). This ~2% efficiency comes from a photonically designed transparency window in the visible spectral range at the NW top cell to achieve current matching with the bottom Si cell.

Ultrathin alumina passivation of perovskite solar cells

(LMPV PhD student Dibyashree Koushik, group Creatore/Kessels TUE)

We have demonstrated that an ultrathin Al_2O_3 layer deposited by atomic layer deposition (ALD) on top of the perovskite absorber substantially enhances both cell efficiency (up to 18%) and its long-term environmental stability (up to 60 days). We have employed in-situ infrared spectroscopy to gain insight into the chemical and structural modifications of perovskite during the deposition of ALD Al_2O_3. Furthermore, we have implemented a high-mobility, highly transparent transparent conducting In_2O_3:H layer grown by ALD onto a perovskite solar cell. The latter exhibits an efficiency of 14.3%, superior to the reference device with ITO as electrode. Furthermore, when the above-mentioned cell serves as top-cell in a four-terminal perovskite/c-Si tandem architecture, a tandem efficiency of 21.3% is achieved.

2. Added value of the programme

The LMPV program acts as a strong team with many collaborations between the four groups. Laboratory equipment, cleanroom facilities and optical characterization tools are shared between groups. Several teams of PhD students/postdocs from different groups work on joint projects.

LMPV progress meetings

The LMPV program holds quarterly *Progress Meetings* at AMOLF. Each meeting has the following schedule:
- Invited presentation by an external speaker from another Dutch university/institute.
- Oral presentation of new LMPV team members presenting their project goal and planning
- Poster session at which all LPMV team members present their work.
- 1-slide oral presentations of all collaborative projects between two or more research groups.
- Plenary discussion on new developments, equipment, collaborations.

LMPV/Nanophotonics colloquia, meetings

The LMPV program is tightly incorporated in the Center for Nanophotonics at AMOLF. This encourages our researchers to incorporate the latest developments in fundamental nanophotonics in solar cell devices. Every week, AMOLF's Nanophotonics department, which is composed of seven research groups including the four LMPV groups, holds the "Nanophotonics colloquium". The program is alternatingly a colloquium in which two PhD students, postdocs or master students give a 45 min. presentation, or a poster session in which every group presents a poster. The seven Nanophotonics/photovoltaics group leaders hold a weekly work lunch to coordinate activities and discuss recent developments. In addition, the four LMPV group leaders hold a bi-weekly meeting to discuss LMPV-related items.

LMPV summer symposia

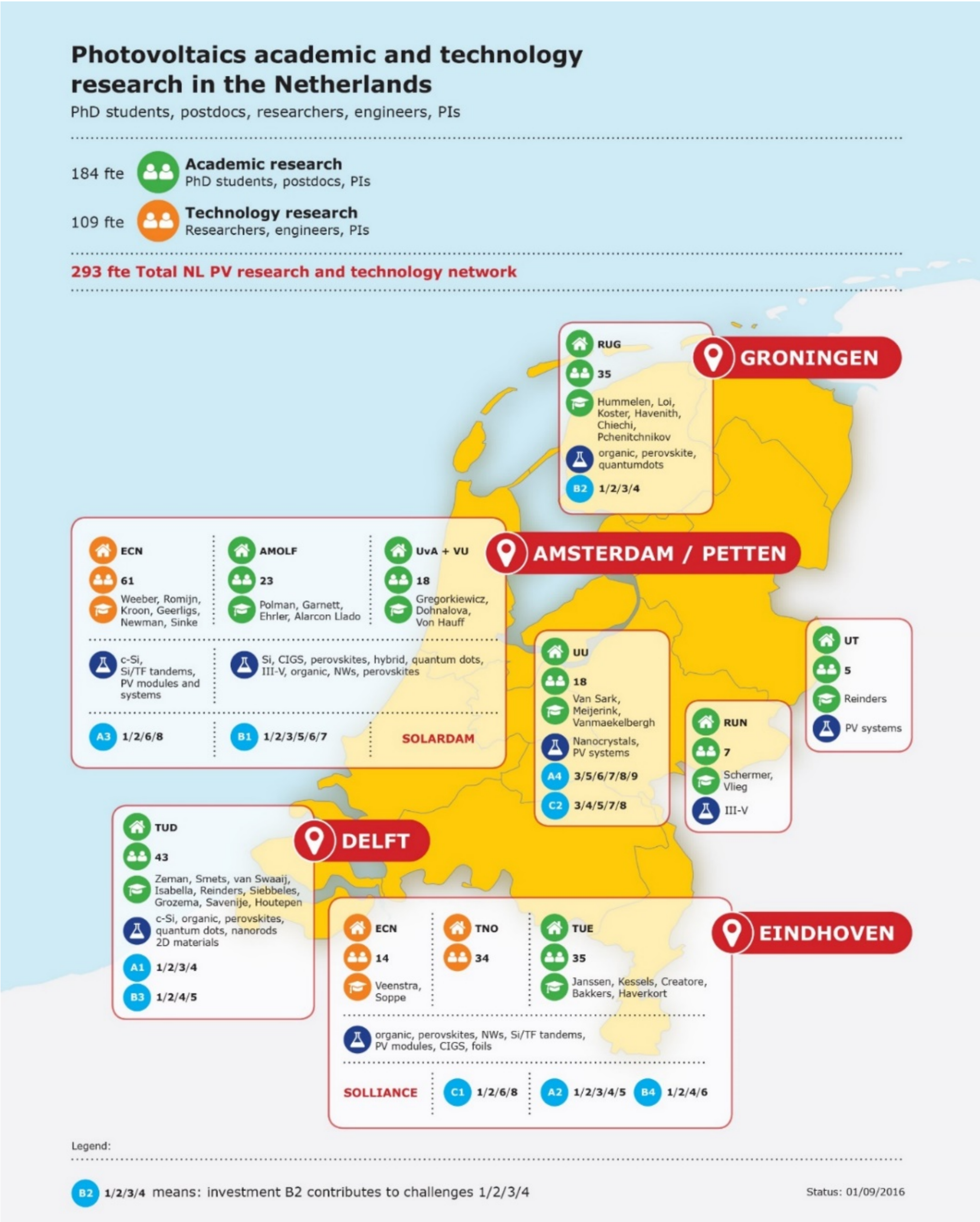
The LMPV program holds a yearly summer symposium at which the entire Dutch PV research community is invited. The three LMPV tenure-track group leaders serve as symposium chairs. The LMPV summer symposium on June 23, 2017 attracted around 100 attendees. Plenary speakers were Harry Atwater (Caltech), Richard Friend (Cambridge University), Frank Dimroth (Fraunhofer Institute), and Martina Schmidt (Univ. Düsburg/Essen). A lively poster session was also held.

National coordination of PV research

One of the programs' goals is to help coordinate PV research in the Netherlands. Coordination can lead to enhanced collaboration between groups across the Netherlands, better sharing of resources, and more efficient transfer of ideas to applications. And in general, coordination increases the visibility and voice of PV science and technology in the Netherlands and abroad.

Albert Polman chaired the report "Dutch Materials – Challenges for materials science in the Netherlands" that now plays a central role in strategic planning of NWO, with "materials for sustainable energy production and storage" as one of the six themes. A Theme Committee Materials Science coordinates the initiatives to start programmatic materials calls within NWO and is composed of Albert Polman (AMOLF, chair), Katja Loos (RUG), René Janssen (TUD), Guus Rijnders (UT), Andries Meijerink (UU), Rolf van Benthem (DSM, TUE), Wim van der Meer (Tata Steel). As a first initiative, the Theme Committee initiated the Program Call entitled "Materials for Sustainability (Mat4Sus)" with a total budget of 9 M€. In January 2018, 15 projects were awarded to groups at WUR, TUD, RUN, TUE, UvA, UL, RUG, UT, UU and AMOLF.

As a parallel initiative a route was established in the National Science Agenda (NWA), entitled "Materials – made in Holland", in which research on photovoltaic materials is one of the key themes. This initiative was carried out by a Steering Committee composed of Albert Polman (AMOLF, chair), Kees Storm (TUE), Daniel Bonn (UvA), Daniel Vanmaekelbergh (UU), Guus Rijnders (UT), Katja Loos (RUG), Marc Geers (TUE), Marjolein Dijkstra (UU), Martin van Hecke (UL, AMOLF), Oscar Goddijn (DSM), Patricia Dankers (TUE), René Janssen (TUE), Sybrand van der Zwaag (TUD), Thom Palstra (RUG) and Wim van der Meer (Tata Steel). The aim of the NWA initiative was to request a major increase in science budget from the government, and (in part) as a result of the effort NWO's budget for fundamental research is now increased by up to 130 M€ per year. NWO will start a new major program round using these new funds and NWO has announced that the NWA routes (including those on Materials and Energy) will be a guiding theme in the distribution of the new funds.



SOLARLab Dutch photovoltaics network coordinated by LMPV. The Dutch PV network is composed of over 180 academic researchers and over 100 research engineers in 4 main hubs: Groningen, Delft, Eindhoven and Amsterdam/Petten. Smaller groups are active in Utrecht, Nijmegen and Enschede. Names of PIs, group size, and expertise, are indicated.

National PV research network SOLARLab

In 2017, LMPV took the initiative to bring together all Dutch PIs in PV research in order draft a joint strategic vision for photovoltaics research in the Netherlands. The 35 PIs represent over 180 PhD students and postdocs at academic institutions, and over 100 technical specialists at ECN and TNO. Two workshops were held at AMOLF to draft a national PV research and investment plan. The new national PV network, named SOLARLab, aims to carry out a joint research program towards ultrahigh-efficiency and low-cost photovoltaics. As a first step an investment proposal was submitted to the National Roadmap for Large-scale Research Infrastructure. Unfortunately, it was not selected for funding. Several other funding options for the national SOLARLab research program are presently being explored.

New projects awarded to LMPV in 2017

NWO research programs provide a unique means for LMPV groups to collaborate with other PV groups in the Netherlands. In 2017, the LMPV team was awarded two projects within the NWO IPP program “Towards high-efficiency hybrid tandem solar cells”, with collaborators at TUD, TUE, UvA, ECN, Shell, Exasun, Eternal Sun, Levitech and Tempress Systems. Within the NWO Mat4Sus program the LMPV team was awarded three projects, in which TUD, TUE, WUR, ECN, Toyota, UNSW (Sydney), Fraunhofer Institute (Freiburg) and Caltech (Pasadena) are partners. A TKI project was awarded stimulating collaboration between LMPV and ECN. Bruno Ehrler was awarded an NWO VIDI grant. Most recently, a proposal was drafted for a new NWO “Free program” entitled “Understanding halide perovskites: a prerequisite to highest solar cell efficiencies”, led by LMPV, with collaborators at TUD and RUG. An overview of all externally acquired projects for the LMPV team for 2017 is given in the Table below. The total amount of project funding acquired by LMPV since the start of the program in 2012 is 13.370 k€. This is 2.5 times the initial FOM/NWO grant.

Funding Agency	PI	Project title	Collaborators	Budget (k€)
TKI Urban energy	Polman	Transparent passivating contact design for advanced solar cells (RADAR)	ECN	50
NWO Joint Solar Program	Polman, Garnett	Towards high-efficiency hybrid tandem solar cells	TUD, TUE, UvA, ECN, Shell, Exasun, Eternal Sun, Levitech, Systems	654
VIDI (NWO)	Ehrler	Why are hybrid perovskites so slow?	-	800
NWO Mat4Sus	Garnett	Direct bandgap SiGe solar cell above the Shockley-Queisser limit	TUE	350
NWO Mat4Sus	Ehrler	Singlet fission-sensitized silicon solar cells	WUR, TUD, ECN, Surfix, Toyota	288
NWO Mat4Sus	Polman	Metasurface solar cells with enhanced functionality	ECN, Fraunhofer ISE, UNSW, Caltech	342
TOTAL				**2.488**

Strategic alliance with ECN/TNO

The LMPV program benefits strongly from a collaboration with ECN, and expert in research and development of silicon solar cells. Earlier, ECN has announced it is planning to move its entire Petten-based solar energy division (>60 researchers and technicians) to Science Park Amsterdam (SPA). The choice for ECN to move to SPA is largely motivated by the strong activities and technical facilities in solar energy research within LMPV, as well as UvA and VU. The move of ECN will bring its advanced wafer-based silicon cell and module processing and characterization facilities, and a strong network of industrial partners to SPA. Pilot production facilities of

Tempress and Levitech will then also move with ECN to SPA. Since these developments, it was decide that ECN will be integrated into TNO. The board of TNO visited the Amsterdam Science Park and the strong case for moving TNO/ECN solar energy to Amsterdam was discussed.

3. Personnel

Since the start of the LMPV program, the personnel has strongly grown. The first three PhD students (Sander Mann, Sebastian Oener, and Freddy Rabouw) funded by LMPV have graduated in 2015/2016 (two *cum laude*) and have left the LMPV program. They have all found postdoc positions at esteemed universities abroad.

Name	Position	Group	New position
Freddy Rabouw	PhD student	Vanmaekelbergh	Postdoc ETH Zurich, (group Norris)
Sander Mann	PhD student	Garnett	Postdoc Univ. Texas, Austin (group Alu)
Sebastian Oener	PhD student	Garnett	Postdoc Univ. Oregon, Eugene (group Boettcher)

Personnel funded by the LMPV grant (situation 2017)

Name	Position	Group	Start date	End date	LMPV grant
Erik Garnett	Group leader	Garnett	1-9-2012		NWO part
Bruno Ehrler	Group leader	Ehrler	1-11-2014		NWO part
Esther Alarcon Llado	Group leader	Alarcón Lladó	1-2-2016		AMOLF part
Tianyi Wang	PhD student	Ehrler	1-12-2014	30-11-2018	NWO part
Dibyashree Koushik	PhD student	Creatore/Kessels	1-6-2015	31-5-2019	NWO part
Mark Aarts	PhD student	Alarcón Lladó	16-6-2016	15-6-2020	AMOLF part
Nasim Tavakoli	PhD student	Alarcón Lladó	16-11-2016	15-11-2020	AMOLF part
Julia van der Burgt	PhD student	Garnett	11-12-2017	10-12-2021	NWO part
Ju Min Lee	Postdoc	Ehrler	1-3-2015	28-2-2018	NWO part
Marc Duursma	Technician	LMPV	1-1-2015	31-3-2019	NWO part
Wim Sinke	Advisor (0.1 fte)	Polman	1-4-2013		NWO part

Personnel funded by additional PV grants acquired by the LMPV group leaders (2017)

Name	Position	Group	Start date	End date	Grant
Albert Polman	Program leader	Polman	1-9-2011		AMOLF
Parisa Khoram	PhD student	Garnett	1-1-2014	31-12-2017	ERC
Gede Adhyaksa	PhD student	Garnett	16-2-2014	15-2-2018	ERC/COMPASS
Jenny Kontoleta	PhD student	Garnett	1-9-2015	31-8-2019	PHNA
Moritz Futscher	PhD student	Ehrler	1-12-2015	30-11-2019	PNHM
Benjamin Daiber	PhD student	Ehrler	1-9-2016	31-8-2020	TKI
Verena Neder	PhD student	Polman	16-9-2016	15-9-2020	UvA
Harshal Agrawal	PhD student	Garnett	16-10-2016	15-10-2020	VIDI
Christian Dieleman	PhD student	Ehrler	16-1-2017	15-2-2021	AMOLF/ARCNL
Andrea Cordaro	PhD student	Polman	1-9-2017	31-8-2020	UvA
Tom Veeken	PhD student	Polman	16-9-2017	15-9-2021	NWO-Philips IPP
Sarah Brittman	Postdoc	Garnett	16-3-2014	15-3-2017	NWO-Philips IPP
Mark Knight	Postdoc	Polman	1-6-2014	31-5-2017	ERC/GCEP
Eric Johlin	Postdoc	Garnett	12-1-2015	11-1-2017	VIDI
Lai-Hung Lai	Postdoc	Garnett	15-1-2016	28-2-2017	PHNA
Biplap Patra	Postdoc	Garnett	1-11-2016	31-10-2019	VIDI
Nick Schilder	Postdoc	Polman	1-1-2017	31-12-2019	ERC
Sven Askes	Postdoc	Garnett	1-6-2017	31-5-2020	PHNA

Forrest Bradbury	Guest (0.2 fte)	Garnett	1-10-2012	31-12-2017	AUC
Piero Spinelli	Guest (0.2 fte)	Polman	1-12-2017	31-11-2020	ECN
Paula Bronsveld	Guest (0.1 fte)	Polman	1-12-2017	31-11-2020	ECN

4. Publications, conference presentations

10LMPV01

Since the start of LMPV in 2012, 96 articles from LMPV research have been published in peer-reviewed international journals. Below, the papers published in 2017 are listed.

Scientific (refereed) publications

Publications by PhD students and postdocs (underlined) directly funded by LMPV

1. Perovskite nanowire extrusion
   S.Z. Oener, P. Khoram, S. Brittman, S.A. Mann, Q. Zhang, Z. Fan, S. Boettcher, and E.C. Garnett, Nano Lett. **17**, 6557 (2017)
2. Integrating sphere microscopy for direct absorption measurements of single nanostructures
   S.A. Mann, B. Sciacca, Y. Zhang, J. Wang, E. Kontoleta, H. Liu, and E.C. Garnett, ACS Nano **doi**:10.1021/acsnano.6b06534 (2017)
3. Highly transparent singlet fission solar cell with multistacked thin metal contacts for tandem solar cells
   J.M. Lee, M.H. Futscher, L.M. Pazos-Outón, and B. Ehrler, Progress in Photovolt. **doi**:10.1002/pip.2919 (2017)
4. Indirect to direct bandgap transition in methylammonium lead halide perovskite
   T. Wang, B. Daiber, J.M. Frost, S.A. Mann, E.C. Garnett, A. Walsh, and B. Ehrler, Energy. Env. Sci. **10**, 509 (2017)
5. Controlling crystallization to imprint nanophotonic structures into halide perovskites using soft lithography
   S. Brittman, S.Z. Oener, K. Guo, H. Aboliņs, A.F. Koenderink, and E.C. Garnett, J. Mater. Chem. C **5**, 8301 (2017)
6. Monocrystalline nanopatterns made by nanocube assembly and epitaxy
   B. Sciacca, A. Berkhout, B.J.M. Brenny, S.Z. Oener, M.A. van Huis, A. Polman, and E.C. Garnett, Adv. Mater. **doi** 10.1002/adma.201701064 (2017)
7. Nano-antenna enhanced two-focus fluorescence correlation spectroscopy
   L. Langguth, A. Szuba, S.A. Mann, E.C. Garnett, G.H. Koenderink, and A.F. Koenderink, Sci. Rep. **7**, 5985: 1-9 (2017)

Publications by PhD students and postdocs funded by research grants acquired by LMPV group leaders (underlined)

1. Direct observation of halide migration and its effect on photoluminescence of methylammonium lead bromide perovskite single crystals
   Y. Luo, P. Khoram, E.C. Garnett, and D. Fenning, Adv. Mater. **29**, 1703451 (2017).
2. Halide perovskite 3D photonic crystals for distributed feedback lasers
   S. Schünemann, S. Brittman, K. Chen, E.C. Garnett, and H. Tüysüz, ACS Photon. **4**, 2522, (2017).
3. Colored solar modules using integrated pixelated resonant dielectric nanoscatterer arrays
   V. Neder, S.L. Luxembourg, and A. Polman, Proc. EU-PVSEC Conference (2017), p. 34, **doi**:10.4229/EUPVSEC20172017-1AO.3.5
4. Conductive-probe atomic force microscopy as a characterization tool for nanowire-based solar cells
   D. Mikulik, M. Ricci, G. Tutuncuoglu, F. Matteini, J. Vukajlovic, N. Vulic, E. Alarcon Llado, A.Fontcuberta i Morral, Nano Energy **41**, 566 (2017)
5. Modeling the performance limitations and prospects of perovskite/Si tandem solar cells under realistic operating conditions
   M.H. Futscher and B. Ehrler, ACS Energy Lett. **doi**:10.1021/acsenergylett.7b00596 (2017)

6. Visual understanding of light absorption and waveguiding in standing nanowires with 3D fluorescence confocal microscopy
R. Frederiksen, G. Tütüncüoglu, F. Matteini, K.L. Martinez, A. Fontcuberta i Morral, and E. Alarcon Llado, ACS Photon. **doi**:10.1021/acsphotonics.7b00434 (2017)
7. Nanoscale back contact perovskite solar cell design for improved tandem efficiency
G.W.P. Adhyaksa, E. Johlin, and E.C. Garnett, Nano Lett. **doi**:10.1021/acs.nanolett.7b01092 (2017)
8. Efficient colored silicon solar modules using integrated resonant dielectric nanoscatterers
V. Neder, S.L. Luxembourg, and A. Polman, Appl. Phys. Lett. 111, 073902 (2017)
9. Large-area nanoimprint by substrate conformal imprint lithography (SCIL)
M.A. Verschuuren, M. Megens, J.F. Ni, H. van Sprang and A. Polman, Adv. Opt. Tech. **6**, 243 (2017)
10. Concepts for external light trapping and its utilization in colored and image displaying photovoltaic modules
L. van Dijk, J. van de Groep, L.W. Veldhuizen, M. Di Vece, and R.E.I. Schropp, Prog. Photovolt.: Res. Appl. **25**, 553 (2017)
11. Light trapping in crystalline silicon and thin-film solar cells by nanostructured optical coatings
P. Spinelli, B.K. Newman, and A. Polman, in: "Nanotechnology for Energy Sustainability", B. Raj, M. van de Voorde, Y. Mahajan (Eds.), Wiley, ISBN: 978-3-527-34014-9 (2017), p. 163
12. Interfacial engineering of metal-insulator semiconductor junctions for water oxidation
I. Digdaya, G. Adhyaksa, B. Trześniewski, E. Garnett, and W. Smith, Nature Comm. **doi**: 10.1038/ncomms15968 (2017)
13. Benchmarking photoactive thin-film materials using a laser-induced steady-state photocarrier grating
L.W. Veldhuizen, G.W.P. Adhyaksa, M. Theelen, E.C. Garnett, and R.E.I. Schropp, Prog. Photovolt.: Res. Appl. **25**, 605 (2017)
14. Visible light, wide-angle graded metasurface for back reflection
M. Estakhri, V. Neder, M.W. Knight, A. Polman, and A. Alù, ACS Photon. **4**, 228 (2017)
15. A silicon-singlet fission tandem solar cell exceeding 100 percent external quantum efficiency
L.M. Pazos-Outón, J.M. Lee, M.H. Futscher, A. Kirch, M. Tabachnyk, R.H. Friend, and B. Ehrler, ACS Energy Lett. **2**, 476 (2017)
16. Opto-electronic enhancement of ultrathin CIGS solar cells
G. Yin, M.W. Knight, M.C. van Lare, M. Solà Garcia, A. Polman, and M. Schmid, Adv. Opt. Mater. **5**, 160063 (2017)
17. 3D Multi-energy deconvolution electron microscopy
M. de Goede, E. Johlin, B. Sciacca, F. Boughorbel, and E.C. Garnett, Nanoscale **9**, 684 (2017)

Invited talks at international conferences/workshops

1. E.C. Garnett, *Nanoscale Solar Cells*, ACS Conference, San Francisco, USA, April 6, 2017
2. E.C. Garnett, *Nanoscale Solar Cells*, MRS Conference, Phoenix, U.S.A., April 18, 2017
3. E.C. Garnett, *Nanoscale Solar Cells*, Next-Gen III: PV Materials, Groningen, July 4, 2017
4. E.C. Garnett, *What can Nano really do for PV?*, Beilstein Syposium on Nanotechnology, Postsdam, Germany, November 23, 2017.
5. B. Ehrler, *Indirect-to-direct bandgap transitions in halide perovskites,* EU PVSEC 2017, September 25, 2017 (opening scientific plenary talk)
6. B. Ehrler, *The sobering reality of perovskite/Si tandem solar cells under realistic operating conditions,* Dutch Perovskite Workshop, Groningen, July 6, 2017
7. W.C. Sinke, *Photovoltaics (PV): science and technology for terawatt-scale deployment,* Karlsruhe Days of Optics and Photonics, Karlsruhe, Germany, November 8, *2017 (plenary)*
8. W.C. Sinke, *One size no longer fits all; PV from low cost to high value,* Symposium "Photovoltaics | Forms | Landscapes" @ EUPVSEC33, Amsterdam, September 26, 2017.
9. W.C. Sinke, *Renewables towards impact; innovation for large-scale deployment* EFA Sustainable Energy Conference 2017, Leeuwarden, October 27, 2017 (plenary),
10. W.C. Sinke, *Photovoltaics: towards ultra-low cost and new applications*, African Solar Energy Network (ANSOLE) Days 2017, Hammamet, Tunisia, May 7, 2017 (plenary)

41 additional presentations were given by LMPV staff at (inter)national conferences, workshop, universities and institutes.

Awards

1. Research into the Science of Light Prize, European Physical Society (A. Polman)
2. Frew Fellowship, Australian Academy of Sciences (A. Polman)
3. Highly Cited Researcher 2017, Web of Science (A. Polman)
4. SolarPower R&D Award, Angel Business Communications (V. Neder; Polman group)
5. Rubicon Fellowship (University of Texas, Austin, USA) (S.A. Mann, Garnett group)
6. Winton Scholarship (Cambridge University, England) (H. Abolins, Garnett group)
7. EPSRC Studentship, Engineering and Physical Sciences Research Council (UK) (H. Abolins, Garnett group)

Conference organisation

1. E. Alarcón Lladó, Organizer, Symposium at Materials Research Society Spring Meeting 2017, Phoenix, USA.

4. PhD defenses

None in 2017

5. Valorisation, outreach and patents

Collaborations with industry

1. Research contract with Philips Research on nanophotonics, Industrial Partnership Program Nanophotonics for Solid State Lighting.
2. Research contract with Philips Group Innovation IP&S, soft imprint lithography.
3. Research contract with Delmic B.V, Delft, cathodoluminescence imaging spectroscopy.
4. Research contract with ThermoFischer/FEI on time-resolved cathodoluminescence imaging spectroscopy.
5. Research contract with ECN on light management in solar cells.
6. Research contract with Global Climate and Energy Program (GCEP, Stanford University), funded by ExxonMobil, GE, Schlumberger, and Toyota.
7. Research contract with Shell, Exasun, Eternal Sun, Levitech and Tempress Systems on development of Si-based tandem solar cells.
8. Partner in Silicon Competence Center, TKI Solar Energy-funded facility with Tempress, Levitech, Eurotron, Roth &Rau, ASMI and ECN.
9. Board Member, TKI Urban Energy (national Public-Private Partnership for energy innovations in the urban environment) (W.C. Sinke).
10. Dutch Solar Design prototype solar modules (see http://www.dsd-pv.nl/).
11. Joint project with DSM, ECN and Oxford PV on singlet fission solar cells.

Demonstrators/prototypes

1. Metal nanowire transparent conducting coatings for photovoltaics.
2. Time-resolved cathodoluminescence imaging system.
3. Colored photovoltaic minimodules.
4. Solar light diffuseness meter for solar panel test field
5. Singlet-fission parallel tandem Si solar cell

Patent applications

1. A. Rao, B. Ehrler, R.H. Friend, and M. Tabachnyk, “Composite light harvesting material and device” US Patent App. 15/326,197

Teaching, master's theses, bachelor's theses

To train a new generation of students in the field of photovoltaics, LMPV group leaders, together with prof. Tom Gregorkiewicz (UvA) teach the PV class within the master program *Advanced Materials and Energy Physics* (AMEP). The class is taken by students from the University of Amsterdam and the Free University Amsterdam. In 2017, some 20 students have followed the course. Furthermore, in 2017 6 master students and 5 bachelor's students completed a research project at AMOLF within the LMPV program.

Outreach, newspapers, radio, television

Several outreach activities were held, most notably presentations at the AMOLF Open Day, and lab tours for numerous visitors to AMOLF: politicians, science policy makers, high school students, etc. Furthermore, LMPV research was reported in national newspapers, on radio and television:

1. W.C. Sinke, De Universiteit van Nederland: public lecture *Hoe halen we zoveel mogelijk energie uit de zon?*, February 8, 2017.
2. B. Ehrler, Primary school presentation on solar energy, organised by "De Jonge Akademie" February 14, 2017
3. W.C. Sinke, De Kennis van Nu: De Kracht van Zonne-energie, VPRO, February 16, 2017.
4. *Solar panels are going green*, NBC News MACH, August 17, 2017
5. *Zonnepanelen worden groen dankzij nanodeeltjes*, NRC, August 19, 2017
6. *Betere zonnecellen zijn nog niet veel beter*, BNR Nieuwsradio, August 23, 2017,
7. *Op Nederlands dak valt opbrengst van veelbelovende 'superzonnecel' nog tege*n, Volkskrant, August 24, 2017
8. *Perovskiet zonnecellen maken beloftes nog niet waar in bewolkt Nederland*, Solar Magazine, August 25, 2017
9. A. Polman, *Zonne-energie breekt door*, Radio Swammerdam, Amsterdam, October 1, 2017
10. A. Polman and W.C. Sinke, *Oranje boven, down unde*r, VPRO, October 12, 2017
11. A. Polman, T*he sun rises for free*, public lecture, Monash University, Melbourne, Australia, November 27, 2017.
12. N.J. Schilder, Nationale Wetenschapsquiz, VPRO, December 26, 2017
13. W.C. Sinke: various contributions to newspapers
14. Various internet publications

Solar test field

A solar panel test field was installed near the AMOLF building. It is composed of 24 panels of 6 different types, including high efficiency Si, CIGS and CdTe. A data logging system is continuously recording the IV characteristics of each panel type, the solar influx (spectrum, intensity), and the associated weather conditions. The data is being made available online and forms the source of projects for bachelor and master students from UvA and Amsterdam University College and elsewhere (see above). The data is licensed under a Creative Commons Attribution 4.0 International License.

6. Vacancies

For the remaining part of the LMPV program budget is available for 3 new PhD projects, one each in the groups of Garnett, Ehrler and Alarcon Llado. The position in the Garnett group has been filled (J.S. van der Burgt). Ehrler and Alarcon Llado are presently recruiting. Furthermore, budget is remaining to organize the yearly LMPV workshop (for which registration is free for participants) until 2020 and to cover the part-time salary (0.1 fte) of Prof. Wim Sinke until 2020.

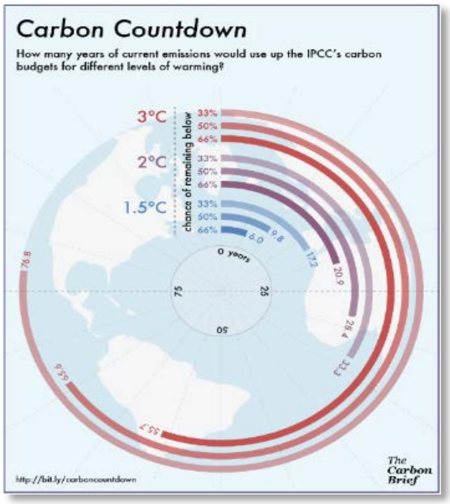
7. Future of PV and LMPV

LMPV was funded in response to an initiative started by FOM to strengthen research on renewable energy in the Netherlands. The transition of our society to a durable energy system is gradually taking place and it is now completely clear that photovoltaics will play a major role in this. PV is a major industry which already has a turnaround of over 100 billion € per year and there is no doubt it will grow much further in the coming years. For PV technology to break through at a major scale, so that it can economically outperform energy generated by fossil fuels, the following very ambitious targets must be reached:

- A further cost reduction of PV electricity generation by a factor ~4 or more, making PV a fully competitive source of electricity. This requires very high PV conversion efficiencies and, thus, the development of fundamentally new PV energy conversion concepts, materials and device architectures. Moreover, it requires low material consumption and ultra-fast processing, enabled by the use of ultra-thin layers and novel fabrication methods.
- Development of new solar applications using tailored PV elements in order to efficiently and attractively integrate PV into buildings, infrastructure and landscape. Keywords are: flexible/low weight, (semi)transparent, freedom of shape, size and color. These technologies must be affordable and designed for sustainability.

These targets cannot be achieved by a simple extension and/or optimization of existing PV conversion concepts and technologies. Instead, they require fundamental breakthroughs in physics, chemistry, materials science and engineering.

The base funding for the LMPV program (FOM/NWO program 131 for which this report is made) will formally come to an end in 2020. After that, AMOLF will cover the salaries of the group leaders from its mission budget. Given the key importance of PV technology and the investments made in LMPV so far (three new research groups, equipment, investments) it is important that long-term energy-related program opportunities become available within the NWO domain ENW, NWO-coordinated programs funded by the NWA, and energy programs of the Ministry of Economic Affairs and Climate. The newly founded national SOLARLab consortium is also aimed to help leverage such funding.



CO_2 countdown clock. Only 7 years of CO_2 emission are left to keep the average temperature rise on earth limited to 1.5°C. Photovoltaics can beat all forms energy generated by fossil fuels if the costs/kWh can be reduced a factor 4. Breakthroughs in photovoltaic materials and device research are needed to reach this goal.

Fact sheet as of 1 January 2018

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Overview of projects and personnel

Group Polman

Leader	Prof.dr. A. Polman
Organisation	AMOLF
Project (title + number)	Light management in new photovoltaic materials 10LMPV01

FOM employees on this project

Name	Position	Start date	End date
M.C. Duursma	TP/V	1 January 2015	31 December 2017

Group Garnett

Leader	Prof. dr. E.C. Garnett
Organisation	AMOLF
Project (title + number)	Light management in new photovoltaic materials 10LMPV01

FOM employees on this project

Name	Position	Start date	End date
E.C. Garnett	WP/T	1 September 2012	Permanent contract
J.S. van der Burgt	PhD	11 December 2017	10 December 2021

Group Ehrler

Leader	Dr. B. Ehrler
Organisation	AMOLF
Project (title + number)	Light management in new photovoltaic materials 10LMPV01

FOM employees on this project

Name	Position	Start date	End date
B. Ehrler	WP/T	1 November 2014	31 October 2019 (tenure-track)
T. Wang	PhD	1 November 2014	31 October 2018

J.M. Lee	WP/T	1 November 2016	28 February 2018

Group Alarcon Llado

Leader	Dr. E. Alarcon Llado
Organisation	AMOLF
Project (title + number)	Light management in new photovoltaic materials 10LMPV01

FOM employees on this project

Name	Position	Start date	End date
E. Alarcon Llado	WP/T	1 February 2016	31 January 2021 (tenure-track)
M. Aarts	PhD	1 September 2016	31 August 2020
N. Tavakoli	PhD	16 November 2016	15 November 2020