Newsletter, June 2023

DegradationLab

Advanced centre for testing degradation and failures in new and emerging solar cells

Dear Readers,

*It is our pleasure to welcome you to the 2nd edition of the **DegradationLab Newsletter**! "DegradationLab— Advanced centre for testing degradation and failures in new and emerging solar cells" is an ambitious project implemented by a network of 6 partner laboratories spanning across 4 European countries, namely Cyprus, Belgium, Austria, and Germany.*

Being at the end of the project, through this edition we would like to highlight overall project achievements and activities that took place in the last year of our project.

If you would like to keep up to date with all the latest developments of our project and our next steps as a DegradationLab you can also follow us on the project website and on social media (FB, LinkedIn).

Kind Regards,

The DegradationLab Consortium

European Union
European Regional Development Fund
Republic of Cyprus
Structural Funds of the European Union in Cyprus

DegradationLab

About DegradationLab

The DegradationLab is a newly developed research laboratory at the University of Cyprus, which is an integral part of the Department of Electrical Engineering and the FOSS Research Centre for Sustainable Energy. Its main scope is to contribute to **the accurate characterization of novel and promising new generation solar cells** towards addressing some of the main challenges faced by these new technologies namely regarding their performance degradation, reliability, etc. The vision is to develop a dedicated research hub in Cyprus focusing on the accurate characterization of novel solar cells and mini-modules such as perovskite devices, perovskite tandems, kesterites, chalcohalides, etc. Particular focus is on aspects of **performance degradation, reliability, and long-term stability.** The new research unit brings together three laboratories from the University of Cyprus UCY (the Photovoltaic Technology Laboratory, the Laboratory of Molecular Spectroscopy and the Laboratory of Ultrafast Science) with three European research organizations, namely IMEC (Belgium), the AIT Austrian Institute of Technology (Austria), and the Max Planck Institute for the Science of Light (Germany).

Duration: 4 years

Budget: 999,460 €

6 Partner Labs

The DegradationLab was co-financed by the European Regional Development Fund (ERDF) and the Republic of Cyprus through the Research and Innovation Foundation under the programme 'New Strategic Infrastructure Units - Young Scientists' (Project ID: INFRASTRUCTURES/1216/0043). The laboratory is currently located at two sites in Nicosia: at the main campus in Aglantzia and at Latsia campus.

Objectives

In a nutshell, the main aims of the DegradationLab initiative were:

- To gain a **fundamental understanding of failure development and evolution** in novel solar cell devices, and
- To find ways to accurately, systematically, and reproducibly study such solar cells/modules assisting in the **development of appropriate measurement protocols**.

In more detail, the project objectives were:

- Development of new laboratory infrastructure at the University of Cyprus for studying new generation solar cells/ modules
- The indoor and outdoor investigation of degradation mechanisms of different structure perovskites and perovskites/silicon tandems at ambient and laboratory conditions and using a combination of advanced techniques.
- Addressing the technical and scientific challenges in indoor and outdoor characterization of perovskite-based cells.
- Investigating carrier dynamics and chemical imaging of perovskite-based solar devices before and after degradation in an attempt to understand carrier losses and various decomposition products.
- The correlation between the microscopic investigations of failures with the performance degradation of perovskite-based cells.

Project Achievements

Infrastructure development

We developed the new infrastructure at UCY to study failures in new/emerging solar cell technologies. Desired specifications included: ability to test small-size solar cells up to mini-modules, single-junction and multi-junction devices, suitability for thin film testing (perovskites, organics, etc.), and different light excitation LEDs or lasers to enable mapping of different junctions in tandems. The following equipment is already operational at our laboratory premises.

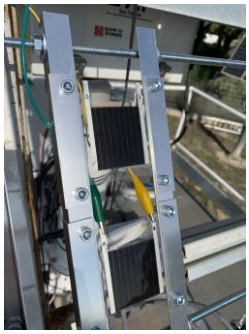
A Sol3A Class AAA steady-state solar simulator (Oriel, Newport) used to test solar cell performance under AM1.5 spectrum.

A LumiSolarCell Electroluminescence (EL) and Photoluminescence (PL) system (Greateyes GmbH) for spatially-resolved measurements of cells (size 0.5x0.5cm^2 to 15x15cm^2) to image micro-cracks, shunts, low lifetime regions, inhomogeneities, etc. **A high-resolution Spectral Response and External Quantum efficiency (EQE) set-up** to measure small-size organic and inorganic cells. **A membrane Nitrogen generator and dessicator** with 11 SCFH flow rate at 99% nitrogen purity (CLEATECH).

A PV-LIT Inspection system Dark Lock-In Thermography and Illuminated Lock-In Thermography with ImageIR 8325 camera (InfraTec GmbH) used for spatially-resolved measurements of cells (size 0.5x0.5cm^2 to 20x20cm^2). The PV-Shunt Inspection System can detect shunts, defects and inhomogeneities in the devices.

A LBIC Economy Light Beam Induced Current system (InfinityPV) for high-resolution spatial mapping of the cell PV response (shunts, inactive areas, etc.) with size 0.5x0.5cm^2 to 30x30cm^2. Additionally, it has EQE spatial mapping capabilities.

An outdoor cell and module performance test bench is used for automated I-V sweeps using a source meter (variation of I-V sweep conditions and bias loading) and monitoring ambient conditions.



In addition to the new systems, a host of techniques was utilized between partner labs to cross-investigate degradation occurring in the perovskite cell devices, including ultrafast spectroscopy, time-resolved PL, resonant Raman spectroscopy, and structural microscopy.

Results – analysis

Perovskite mini-module development

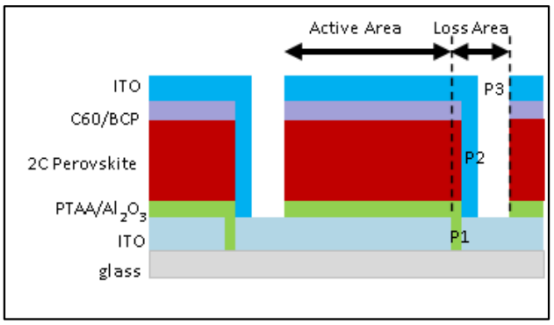
The project foresaw the investigation of different perovskite-based solar devices, mainly mini-modules, in order to study the impact of perovskite composition, architecture, encapsulation, etc. on the performance and stability of the devices. This would enable selection and optimization of devices as well as highlight the appropriate measurement procedures/sequences that need to be followed depending on the sample technology (e.g. appropriate pre-conditioning).

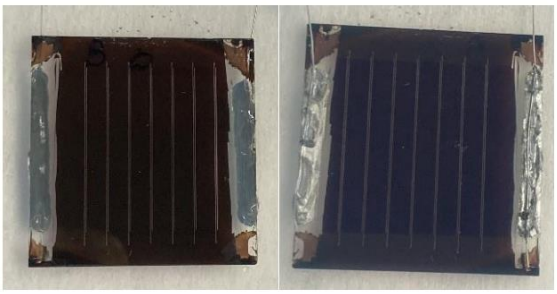
To this end, a number of samples have been developed by IMEC and been studied at the different partner laboratories in order to gain insights into degradation mechanisms and to build experience in good measurement practices for perovskites. Additionally, the samples needed to align to the measurement restrictions/requirements of the different techniques employed in the project which included electrical characterization, field monitoring, Raman measurements, Ultrafast spectroscopy measurements, etc.

In particular, the exploratory approach included:

- Different perovskite layer composition: two-cation perovskites (2C) such as $Cs_{0.18}FA_{0.82}PbI_{2.82}Br_{0.18}$ and three-cation perovskites (3C) with and without formamidinium chloride (FACl) additives
- Different packaging thickness e.g. thin (0.2micron) and thick front glass (2mm)
- Different device architecture: p-i-n structure and n-i-p structure
- Single-junction and multi-junction solar devices (i.e. perovskite on silicon)

Multiple identical modules were studied to obtain better statistical behaviour from same batch devices. The common features of the samples tested were: the use of laser scribing to generate the sub-cells in series (as shown in figures above), the use of ITO to prevent penetration of metallic particles of the top electrode into the soft perovskite layer, the selection of ITO as a top electrode to obtain semi-transparent modules, and the hermetic sealing of the devices using glass packaging to withstand indoor accelerated aging and outdoor conditions.





Indoor optical and electrical characterization

The performance of the perovskite-based samples developed was investigated primarily with the acquisition of steady-state current-voltage (I-V) measurements indoors. The first challenge being addressed in the project is related to the transient nature of the perovskite cells (capacitance effects, ion migration, etc.) which hinders the accurate and reproducible measurement of device efficiency. To this end, efforts were made to

develop (and improve any existing) measurement strategies in order to ensure the accurate perovskite characterization.

Therefore, the impact of different measurement conditions on device performance measurements e.g voltage sweep order i.e. forward- or reverse- scan, voltage sweep rate (see figures above), sample bias loading conditions, pre-conditioning, holding times at start of scan, etc., was extensively investigated for different perovskite technology devices. Although this measurement campaign exhibited some device-dependence, it did verify the appropriateness of some testing conditions in minimizing hysteresis and artifacts in measurements. [DOI: 10.4229/WCPEC-82022-2AV.1.4]

Based on these learnings, the core investigation route followed, as regards indoor performance and stability of the perovskite-based samples, involved primarily the acquisition of steady-state current-voltage (I-V) measurements indoors, EQE measurements, and EL, PL, DLIT and LBIC imaging. Currently the partners are addressing the challenge of obtaining accurate EQE measurements from the whole mini-module active area.

Outdoor field testing

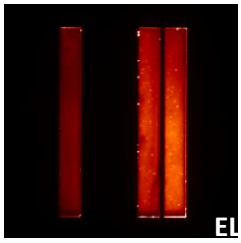
A number of encapsulated modules has been tested in the outdoor test bench (at fixed-plane array) at UCY giving insights into the long-term performance stability of the devices under real operating conditions. Current-voltage characteristics are collected at regular intervals during field testing together with ambient environmental data.

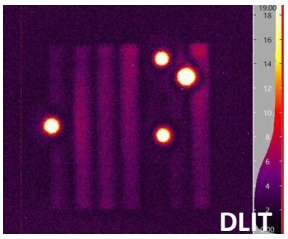
At all times, the degradation of modules tested outdoors is compared with the degradation of the identical control modules kept indoors in order to distinguish the effects of outdoor aging and intrinsic degradation. In most cases, the control modules present very good stability.

In the project, work was performed on comparing performance degradation between samples with and without additives in the active layer, between samples with different encapsulation thickness, between samples with different cation presence in the active layer, etc. Additionally, meta-stabilities in these devices were investigated (diurnal degradation trends and overnight recovery), long-term stability (ranging from some weeks to more than one year), seasonal effects, and the effect of different field operating conditions on the output characteristics of the devices.

Before and after outdoor aging, we used all available (in our project) non-invasive techniques for identifying failures, evolution of failures and reversible effects. Overall, a multiway evaluation was implemented before and after field exposure. This incorporated I-V, EQE, EL, PL, DLIT, LBIC measurements as well as the evolution of Raman and ultrafast

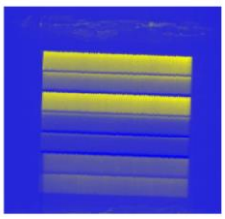
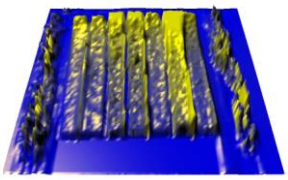
spectra from the test samples which can highlight any changes in device composition and carrier dynamics due to degradation.



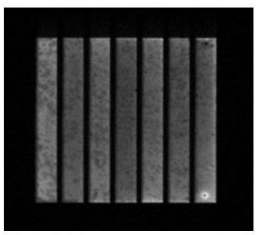
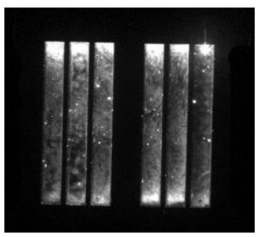
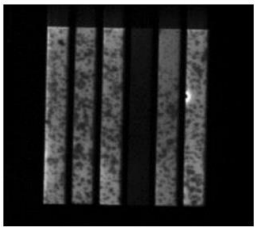
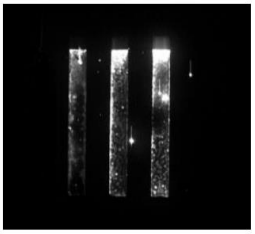


Spatially-resolved measurements from mini-modules such as EL and DLIT images (shown above) were acquired before outdoor aging and at regular intervals during outdoor exposure in order to map the initial degradation state of the samples and the failure evolution with aging.

LBIC images shown below (left: 2D LBIC, right: 3D LBIC) from a perovskite mini-module indicate clearly cells with lower and cells with higher photo-response.

The evolution of degradation in EL images from two mini-modules taken before (left images) and after (right images) 17 weeks of outdoor exposure (link) is shown below.

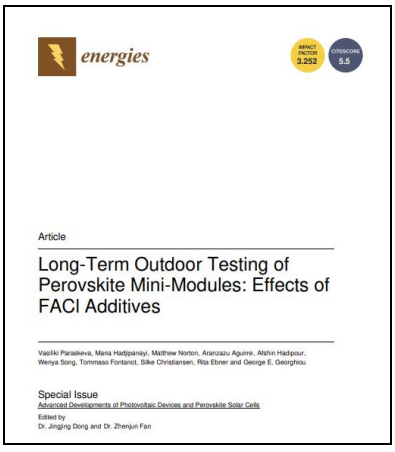
Structural microscopy techniques were also employed to investigate the impact of the outdoor aging on structure and chemistry of the layered architecture of the devices under test. There remains a challenge to overcome which is related to the presence of the encapsulant material and getting access to the device within without allowing for degradation to occur during the 'de-lamination' process. Efforts are still underway for the comprehensive structural analysis of samples (before and after outdoor aging) in order to correlate the opto-electrical and spectroscopic findings with the structural changes occurring in the test devices.

In the section that follows, the Reader can refer to the journal and conference papers generated in the project since 2022 for more information on research outcomes.

Dissemination activities

Journal publication

In March 2023, our outdoor aging results were published in Energies (MDPI). The manuscript is titled '*Long-Term Outdoor Testing of Perovskite Mini-Modules: Effects of FACl Additives*' (V. Paraskeva et al., Energies 2023, *16*, 2608). You can find the manuscript here: Energies link


energies

Article

Long-Term Outdoor Testing of Perovskite Mini-Modules: Effects of FACl Additives

Vasiliki Paraskeva, Maria Hadjipanayi, Matthew Norton, Aranzazu Aguirre, Afshin Hadipour, Wenya Song, Tommaso Fontanot, Silke Christiansen, Rita Ebner and George E. Georghiou

Special Issue
Advanced Developments of Photovoltaic Devices and Perovskite Solar Cells
Edited by
Dr. Jingjing Dong and Dr. Zhenjun Fan

Conferences

The DegradationLab UCY team participated in the 3rd edition of Women in Renewable Energy (**WiRE-2022**) conference which was a satellite event of the European Materials Research Society Conference (E-MRS) (2 of June, 2022, online). Dr. M. Hadjipanayi presented project work on '*Impact of chopping frequency and voltage/light bias during EQE measurements of perovskite/Silicon tandem solar cells'*.

Project findings on the '*Seasonal dependence of diurnal efficiency degradation and recovery in perovskite mini-modules during outdoor testing'* were presented by Dr. M. Hadjipanayi at the **49th IEEE PVSC** conference in Philadelphia, USA (5-10 June 2022). See conference proceedings [link].

Additionally, project researchers from UCY (Dr. M. Hadjipanayi) and from AIT (Dr. R. Ebner) participated in the 8th World Conference on Photovoltaic Energy Conversion 2022 (**WCPEC8**) in Milan, Italy, which took place on 26-30 September 2022. Two visual presentations were delivered titled: '*Evaluation of performance measurements of different type perovskite device' and at different measurement conditions'* [DOI: 10.4229/WCPEC-82022-2AV.1.4] and '*Characterization and degradation of perovskite mini-modules'* [DOI: 10.4229/WCPEC-82022-2AV.1.34].

Dr. R. Ebner (AIT) presented results from the project to the **37th PV-Symposium** in Germany (8-10 March 2022) and to the **PV & ELECTRICITY STORAGE SYMPOSIUM**, organized by the Austrian Photovoltaic Technology Platform and the Federal Association Photovoltaic Austria (5-6 October 2022, Vienna). Poster was titled '*Optische und elektrische Charakterisierung von Perowskiten*'.

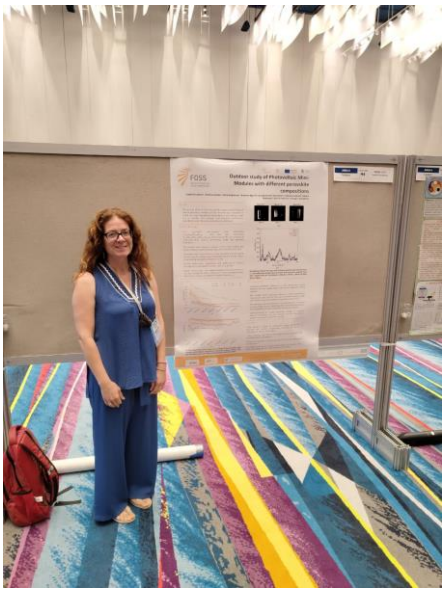
Dr. M. Norton from UCY participated in the 13th International Summit on Organic and Hybrid Photovoltaics Stability (**ISOS13**) which took place on 27-30th September 2022 in

Sonderborg, Denmark. Dr. Norton delivered a poster presentation on research project advancements on outdoor studies of perovskite mini-modules with different perovskite compositions. The aim of this work was to detect any differences in the long-term performance of these devices which can be attributed to their composition.

Dr. M. Hadjipanayi also participated in an online booth of the International Conference on Research Infrastructures 2022 (**ICRI 2022**) whereby the project main infrastructure developed was presented.

Prof. Dr. S. Christiansen presented latest work from the project to the Indo-German Workshop on Developments in Established and Emerging Photovoltaic Technologies (**DEEPT 2023**) (13-15 March 2023, India). Her abstract was titled '*Scale-bridging, multi-modal characterization of metal halide perovskite materials and devices'*.

Dr. R. Ebner (AIT) presented results from the project to the **38th PV-Symposium** in Germany (28 February - 2 March 2023). Her poster was titled *'Charakterisierung und Degradation von Perowskit-Minimodulen'*.



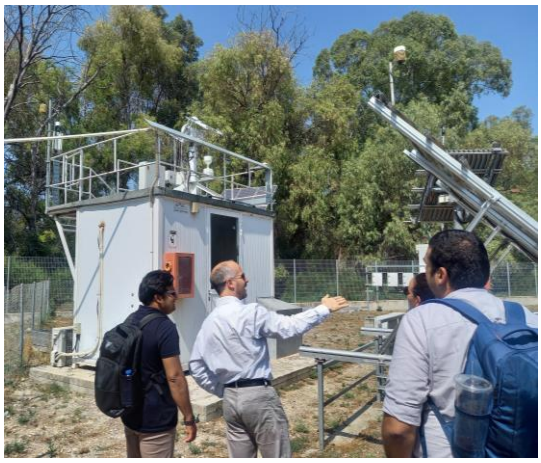
Dr. M. Hadjipanayi presented the latest outdoor results analysis to the **50th IEEE PVSC** conference (11-17 June 2023, Puerto Rico). Her poster title was '*Outdoor study of Photovoltaic Mini-Modules with different perovskite compositions*'.

Outreach and Awareness raising

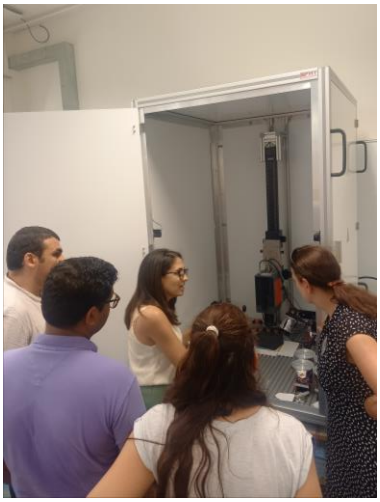
The University of Cyprus organized the **final workshop of the DegradationLab project** within the framework of the European Sustainable Energy Week (**EUSEW**) on the 27th June 2023 at the UCY campus premises in Nicosia, Cyprus.

The event was jointly organized by the DegradationLab project and the TESTARE project (www.testare.eu), which is a Horizon Europe Twinning action (Grant No: 101079488) essentially the continuation of the DegradationLab efforts. Event title: '1st Cypriot PV Workshop: DegradationLab and TESTARE Joint Event'.

Speakers from IMEC, AIT, Fraunhofer ISE, Ben Gurion University of the Negev, Fraunhofer IKTS, University of Cyprus departments as well as from Cyprus University of Technology were invited to present their latest research in new generation PV.



The workshop was intended for the local and international scientific community, industry, enterprises, young researchers, and stakeholders in the PV sector.



Moreover, the attendees had the opportunity as part of an **Open Lab Day** to visit the new DegradationLab facilities developed during the DegradationLab project through guided tours.

Lastly, the DegradationLab team engaged in **outreach activities to school students** through the "Researchers at School" Programme in the context of the research project CONNECT ("Cyprus ON a mission to Engage, inspire and Connect with citizens through the European Researchers' Night") of the Cyprus Research and Innovation Foundation (RIF). Dr. Hadjipanayi, as part of the World Earth Day 2023, presented the research activities of the DegradationLab team to the students of Ayios Dometios and Geri Gymnasiums (April 2023).

What is next for DegradationLab?

Conferences

The DegradationLab UCY team plans to attend the 40th European Photovoltaic Solar Energy Conference & Exhibition (**EU PVSEC 2023**) to be held from 18-22 September in Lisbon with a paper titled '*Correlative microscopy and spectroscopy of perovskite mini-modules: degradation analysis'*.

Additionally, the team will also attend the 6th International Conference on Perovskite Solar Cells and Optoelectronics (**PSCO 2023**) to be held in Oxford from the 18-20 September 2023 with a paper titled '*Learning curves from long-term outdoor testing and indoor optoelectronic characterization of perovskite mini-modules*'.

Inter-comparison campaigns

The DegradationLab UCY team joined international efforts to setup an outdoor ISOS inter-comparison network (after the ISOS-13 workshop in 2022, coordinated by Prof. Eugene Katz from Ben Gurion University of the Negev) and is currently participating in the

global experiment setup to test perovskite-based cells outdoors in different climates in order to gain further insight into their stability and towards developing better test protocols. The experiment is at initial stages and samples are being distributed to interested labs for testing.

New Twinning project

The DegradationLab UCY team is now leading a Horizon Europe Twinning project called 'TESTARE' which is about enhancing the R&I capabilities of DegradationLab in TEsting new generation PV from the perspective of Long-term STAbility and field Reliability. To achieve this, DegradationLab will be twinning with 3 excellent R&I institutions (IMEC, Fraunhofer ISE, and Ben Gurion University of the Negev) in the field learning from them and co-creating with them joint research and much more! TESTARE has a budget of 1.499.996.25 EUR and ends in 2025.

For more information, please visit the TESTARE website

Project Consortium

The PV Technology Laboratory of FOSS Research Centre for Sustainable Energy has an excellent track record in research in the field of solar energy. Its main priority is the development of a R&I portfolio in renewable energy technology, PV performance, degradation/failure analysis, forecasting, energy yield modelling, grid integration, integrated sustainable solutions. The Laboratory has developed advanced infrastructure and capacity in the last 10 years.

The Laboratory of Ultrafast Science is hosted in the UCY Department of Physics and its main objective is to utilize photonics to investigate the physics of interactions in novel materials using various continuous-wave and transient spectroscopic techniques. To this end, the Laboratory has developed over the years a number of state-of-the art experimental ultrafast laser setups.

The Laboratory of Molecular Spectroscopy is hosted in the UCY Department of Chemistry, and is fully equipped for the spectroscopic characterization of thin films. In particular, the laboratory is equipped with a state-of-the-art UV and visible Resonance Raman system.

IMEC (INTERUNIVERSITAIR MICRO-ELECTRONICA CENTRUM) is one of the largest independent R&D centers worldwide in the field of nano-electronics. The Thin Film PV group has a track records of over 15 years in the field of organic solar cells and since 2014 has extended its activities on hybrid, perovskite-based thin film solar cells. IMEC's Thin Film PV group acts in this project as device integrator for cells and modules based on perovskite active layers.

The Austrian Institute of Technology GmbH (AIT) is Austria's largest non-university research organization that works closely with related industry and public bodies in order to create benefits through innovation and new technologies. AIT's Center for Energy offers scientific support in R&D, as well as certified standard testing to PV and PV-related manufacturers all over the world. Moreover, AIT Energy is specialized in the experimental research of reliability, aging, and failure analysis of PV modules, the characterization and modelling of crystalline, thin-film and new PV technologies.

The Max-Planck Institute for the Science of Light (MPL) performs basic research in optical metrology, optical communication, new optical materials, plasmonics and

nanophotonics, optical applications in biology and medicine. It is part of the Max Planck Society and was founded in 2009. The Institute has a strong partnership with the Friedrich-Alexander University of Erlangen-Nuremberg (FAU), with shared resources and equipment for synthesis, modelling, a large variety of characterization including nano-probe and correlative microscopy equipment.

Project website - Social media

Stay informed on the progress and activities of the DegradationLab research unit at the University of Cyprus through the DegradationLab website and our news feeds in Facebook and LinkedIn.

For more information and interest to collaborate, please contact the project coordinator:
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