Publishable JRP Summary Report for JRP ENG51 SolCell
Metrology for III-V materials based high efficiency multi-junction solar cells

Background

Today's energy policies are based on three requirements: the energy should be secure, affordable and sustainable. The solution is likely to be a mix of sources depending of the country and the market conditions. In the energy offer, photovoltaics (PV) have grown at a phenomenal rate of over 40% per year for the last decade. This was mostly driven by government subsidies and the lowering cost of silicon based solar cells. This is however not sustainable, both financially and in terms of power requirement. This project supports an emerging offer in the solar energy sector that requires far less area per kilo-watt-hour produced and has the potential to be sustainable without government subsidies.

Concentrated photovoltaics (CPV) use relatively cheap optical elements to concentrate the sun light onto highly efficient multi-junction solar cells (MJSC). III-V materials based MJSC structures are designed so that each junction absorbs a separate portion of the solar energy spectrum, allowing for solar energy conversion with efficiencies as high as 44%. The technology is rapidly advancing from a proven space technology to terrestrial application. A key element for the technology to compete with existing traditional energy sources is to further increase the cell efficiency to 50% or higher.

Need for the project

III–V MJSC structures are made of a high number of layers, which makes a pure experimental optimization difficult and expensive; this also limits the uncertainty of cell calibration due to the complexity of their spectral response. Beside the complexity of the structure, there is a dramatic lack of reliable material properties data for the compound semiconductors used in these cells: discrepancies about 30% are currently observed between measured and modelled efficiencies. The industrial sector and academic research require accurate and spatially resolved metrology to determine traceable and complete III-V material data sets: structural, optical, electrical, optoelectronic and thermionic properties are required. There is also a need to develop metrological tools to quantify the transport mechanisms, the influence of quantum confinement and interfacial effects in these structures to accelerate their market adoption.

Rating the performance of PV modules is critical for determining the cost per watt, and efficiency is useful to assess the relative progress among PV concepts. To date, only MJSC with a maximum of three active layers can be calibrated in NMIs across Europe. For these systems, lower calibration reproducibility and higher uncertainties are obtained in comparison with primary silicon reference solar cells investigated for instance by differential spectral responsivity (DSR). With the next generation of multi-junction solar cells already in production it is urgent to work towards new standards and lower the uncertainty in measurement of MJSC efficiency.

Increasing the number of junctions, using innovative nanostructures or coupling PV with other harvesting technology such as thermoelectric could in theory increase the conversion efficiency as high as 80%. The metrological tools needed to develop this next generation of solar cells and migrating from the expensive Ge substrate to cheaper Si one also need to be investigated.

Scientific and technical objectives

The objective of this project is to develop traceable metrological infrastructure in support of the rapid advances made on multi-junction solar cells that are based on III-V materials. The work program is aiming at developing techniques and methodologies to enable traceable and accurate characterisation of structural, optical, electrical, optoelectronic and thermionic properties of III-V material based MJSC, from the macro to

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nanoscale, in order to enhance efficiency of present devices and enable the production of next generation solar cells.

The project addresses in detail the following scientific and technical objectives:

- To develop methods to accurately measure electrical transport properties of III-V complex heterostructures: band-gap, work function, dopant distribution, photocurrent, carrier density, diffusion length, doping dependent minority carrier lifetime, absorption coefficients and series-resistances. Accurate measurements of these physical parameters are of particular importance to deeply understand the electrical transport phenomena in these heterostructures;
- To characterise composition, thickness, structural and optical properties of III-V material in order to highlight the effect of defects concentration, microstructure and interfaces on the recombination mechanisms of charge carriers;
- To measure carrier transport between interfaces in MJSC and to characterise narrow tunnel-junction properties;
- To develop reliable tools and workflows to measure size dependent electronic structures of nanostructured semiconductor quantum dots;
- To measure thermoelectric properties of III-V material and thermal transport across interfaces; and
- To develop traceable and reliable calibration methods, and standards for determining device efficiency, linearity, temperature dependence and spectral responsivity of MJSC devices.

Expected results and potential impact

Methods to accurately measure electrical transport properties of III-V complex heterostructures

Characterisation of material properties layer by layer have started on samples distributed during the first six months of the project: single-junction and dual-junction structures lattice-matched to GaAs; and relevant sample preparation standard operating procedure have been developed and successfully reproduced. The initial focus has been on consistent sample handling and preparation.

A series of excellent results have been obtained based on new facilities developed at NPL for the nanoscale electrical characterisation of III-V samples. Successful implemented methods are: Scanning Kelvin Probe in air and in ultra-high vacuum and scanning spreading resistance (SSRM). Uncertainty budget and proper quantification of results are under way.

Full wafer microwave measurements have been performed. Low-energy secondary ion mass spectrometry (SIMS) has also been used to identify doping in the layers. Sample preparation methods for scanning probe techniques have been extended to a well document methods to prepare sample for electron beam cross section analysis. Scanning Microwave Microscopy have been successfully completed on all samples. Spatial and spectrally resolved electroluminescence (EL) measurements in a wafer autoprobe station has also been implemented.

Characterising composition, thickness, structural and optical properties of III-V material

Composition characterisation of samples using low energy SIMS, with enhanced depth resolution and determined layer composition in GaAs layers and cathodoluminescence (CL) have been completed; and high resolution x-ray diffraction has been used to measure composition and layer thicknesses in multilayer structures, including AlGaAs and GaInP layers closely lattice-matched on GaAs.

To enable us to measure reflected light from the anti-reflection coating, a high gain, low noise and traceable transimpedance amplifier has been developed for measuring photo detector currents with a resolution of 10 fA, with an adjustable gain from 10^3 to 10^{11}. An Agilent Cary 7000 spectrophotometer has also been purchased and commissioned to enable us to carry out reflectance measurements.

Measuring carrier transport between interfaces in MJSC and characterising narrow tunnel-junction properties

Different devices have been fabricated by the partners, such as MJSC devices and III-V test structures based on silicon, beryllium and copper doped GaAs and AlGaAs alloys grown on either semi-insulated or doped GaAs substrates, and have been distributed among the project partners for characterisation.

Measuring size dependent electronic structures of nanostructured semiconductor quantum dots

InAs-based Quantum Dot (QD) samples grown on GaAs have also been fabricated, presenting two stages of QDs, each one with a density of about 2.7e10 cm^{-3}. A first sample has now been prepared for measurement of distribution and film roughness.

Measuring thermoelectric properties of III-V material and thermal transport across interfaces

A model to describe thermal transport in III-V multilayers is currently being developed. A series of experiments demonstrating large noise sensitivity in the measurement has started; and a new set-up based on an infra-red camera have been developed to monitor heat loss at the microscale during current transport. A new facility to measure with more accuracy the thermal conductance of solar cells and related wafers has been developed by NPL

Developing traceable and reliable calibration methods and standards

We have done very good progress on the development of a world-unique facility to calibrate multijunction solar without the need for expensive and rare balloon flight. PTB has developed a set of synthetic calibration methods with an uncertainty close to 0.6%.

Experiments on MJSC and component cells have continued. After the reduction in calibration uncertainty in component cells, a photocurrent linearity evaluation was performed. The temperature dependence of the open circuit voltage in MJSC was also successfully determined; and a series of experimental studies for the next steps in MJSC calibrations were executed. A goniometric reflectance setup has been modified for use with component cells and MJSC; and a differential spectral responsivity setup has been realised and tested. Elsewhere, monochromatic bias towers have been constructed, assembled and tested and the gained experience will now be transferred for implementation of monochromatic light sources in the differential spectral responsivity setup.

A project website was set up in September 2014 and is regularly updated with information from the consortium, collaborators and stakeholders. The stakeholder committee so far consists of 8 members, including 7 industrial partners who are strongly engaged in the photovoltaic and semiconductor industries. It is important to highlight that a number of stakeholders (Azurspace, III-V labs and Thales) made the effort to come to Madrid for the first year meeting. The consortium is very grateful for their contribution and effort. Separately, NPL is keeping close contact with IQE which has reiterated their support of the project.

A network of European end users strongly interested in the project is also currently being formed to express end user needs and concerns. An early uptake of the project output by one of the end users is the Finnish solar simulator manufacturer Endeas Oy, who are using the expertise of the project partners to solve their recurrent problems with uniformity measurements.

The former project coordinator has joined the National standardisation Committee UF82 ‘Systèmes de conversion photovoltaïque de l’énergie solaire’ with the aim of identifying different needs for standardisation, to which the project could contribute (the former coordinator staying currently in contact with the present coordinator). Another of the partners, PTB, also has a member on IEC TC-82 and has participated in the process for the creation of standard IEC 60904-1- (Photovoltaic devices - Part 1: Measurement of photovoltaic current-voltage characteristics). A project member has also attended the IEC Loughborough meeting of TC-82:WG 2 where the creation of standards IEC 60904-1-1 and IEC 60904-1-8 was further discussed.

The project has been presented in number of high profile international conference: MRS Spring Meeting 2015, 10th European Space power Conference, 29th European Photovoltaic Solar Energy conference 2015, the Solar Energy UK Conference 2014, the Frontier of Characterization and Metrology for Nanoelectronics 2015 and at the international Conference on Precision Electromagnetic Measurements (CPEM) in Brazil.

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