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 sunlight 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 pure experimental optimisation 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 of 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 and to influence the 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 to migrate from the expensive Ge (Germanium) substrate to the cheaper Si (Silicon) substrate also needs 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 aimed 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, and 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

It has been demonstrated that a 50 nm lateral resolution could be achieved by scanning across a tunnel diode (width <50 nm) in TAN sample. An algorithm based on three known standards has been developed. This allows one to extract dopant densities of semiconductor layers. For proper references, the accuracy can be even below 10%. In the continuation of the successful Scanning Microwave Microscope (SMM) based measurements carried out on GaAs staircase dopant density sample, dopant densities have been determined. The results agree very well with that obtained from Secondary Ion Mass Spectrometry (SIMS) techniques. A thermal model of transport between the layers of III-V MJSC has been developed. Based on the available data for thermal conductivity of the different materials, it was predicted than no significant thermoelectric energy recover would be possible in the MJSC.

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

Results of ellipsometric modelling performed on single and dual solar cells show a general good agreement with expected thickness values but highlights the poor sensitivity of ellipsometry to thin buried layers in the case of very complex stacks such as dual junctions. In the meantime the temperature dependence of the optical constants of AlGaAs layers has been extracted from ellipsometry measurements between 20°C and 220°C. Spectroscopic ellipsometry based measurements have also enabled to determine optical properties of GaInAsN test structures.

A method has been developed to determine temperature-invariant band gap energy for III-V opto-semiconductors. The method has been verified to work with all III-V optosemiconductor compounds. The spectral responsivity and normalized emission spectrum for the GaAs/GaInP solar cell have been obtained.

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

Based on the model published in 2016, extensive numerical simulations were carried out on different types of tunnel junction structures. The band structure modification due to the high doping was highlighted and its effect of the tunnel mechanism was quantitatively evaluated. The improved simple model was confronted and shows good agreement both with experimental measurements and with a full quantum model developed by IM2NP in Marseille, France.

Extending measurement facilities to perform multi-junction solar cell calibrations

An LED based sun simulator has been completed and tested. The first characterization experiments on this new device show promising first results and the investigation of 3J-MJSC with this device began.

Output and Impact

The project is closely involved with all the European key players in the field of multijunction solar cells. These companies form the stakeholder committee and are closely following the project through interaction with their respective NMI's or by assisting at various progress meeting. They recognize the importance of the recent results of the EMRP ENG-51 project and plan to utilize standards which are synthetically calibrated with the methods developed in this project within their metrology department.
All members of the consortium have also been actively involved with their respective national companies and researchers, resulting in a large number of interaction and presentation in national and international conferences.

JRP start date and duration:	01 July 2014, 36 months
JRP-Coordinator: François Piquemal, Dr, LNE Tel: +33 1 3069 2173 E-mail: francois.piquemal@lne.fr JRP website address: http://projects.npl.co.uk/solcell/	
JRP-Partners: JRP-Partner 1 LNE, France JRP-Partner 2 INTA, Spain JRP-Partner 3 METAS, Switzerland JRP-Partner 4 MG, Poland JRP-Partner 5 VTT, Finland JRP-Partner 6 NPL, UK JRP-Partner 7 PTB, Germany	JRP-Partner 8 TUBITAK, Turkey JRP-Partner 9 AGILENT Austria, Austria JRP-Partner 10 AZUR SPACE, Germany JRP-Partner 11 FhG, Germany JRP-Partner 12 CEA, France JRP-Partner 13 CNRS, France
REG-Researcher (associated Home Organisation):	Christophe Licitra CEA, France
REG-Researcher (associated Home Organisation):	Guilhem Almuneau CNRS, France
REG-Researcher (associated Home Organisation):	Diego Alonso Alvarez IC, UK

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