Final Publishable JRP Summary for 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 (i) secure, (ii) affordable and (iii) sustainable. The use of photovoltaic (PV) silicon solar cells has grown rapidly at a rate of 40% per year over the past decade. However, this rapid growth is mainly as a result of government subsidies and a reduction in the cost of PV silicon-based solar cells. Therefore, it is unsustainable financially, and also because the silicon used in the PV solar cells is unable to provide the required energy conversion efficiency alone (i.e. the ability to convert solar energy to electrical energy).

Multi junction solar cells (MJSC) are solar cells made of layers of different semiconductor materials. They are designed so that each junction of materials produces an electric current in response to different wavelengths of solar light. The use of multiple semiconducting materials in MJSC allows the absorbance of a broader range of wavelengths, improving their ability to convert sunlight to electrical energy when compared with existing PV silicon solar cells.

Prior to this project, the materials that made up MJSCs enabled a solar energy conversion efficiency of up to 44 %. However, if MJSCs are to be able to compete with traditional energy sources (i.e. nuclear, coal etc), their efficiency needs to reach at least 50 %. This project reduced the cost of generating electricity from PV by developing the metrological tools required to increase the efficiency of current MJSCs, while improving manufacturing processes and materials. This will enable the production of the next generation of solar cells using MJSCs.

Need for the project

Concentrated photovoltaics (CPV) is an emerging technology 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. CPV uses relatively cheap optical lenses to concentrate sunlight onto highly efficient MJSC made from III-V materials, so called III-V because these semiconductor elements are in groups III and V of the periodic table of chemical elements. III-V semiconductor materials display a range of useful properties, including a sensitivity to both heat and light, making them ideal for use in PV solar cells.

In the last two decades, CPV based on MJSC have rapidly advanced from a proven space-based technology to terrestrial applications, however a key requirement for the technology to compete with existing traditional energy sources is to further increase the solar cell efficiency to 50% or higher, a value that is considered as a tipping point for wider commercial acceptance by industrial experts.

III-V materials based MJSC structures are complex, and prior to this project it was difficult to characterise their performance (and solar energy efficiency) with the required accuracy. In addition, there was a lack of reliable material properties data for the compound semiconductor materials used; i.e. discrepancies of around 30 % were observed between measured and modelled solar cell energy efficiencies.

In order to accelerate their market adoption, accurate measurements to determine traceable and complete III-V material data sets are needed, including their structural, optical, electrical, optoelectronic and thermionic (thermally induced flow of charge carriers) properties. There is also a need to develop metrological tools to quantify III-V material electrical transport mechanisms.

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Rating the performance of PV solar cells is critical for determining the cost per unit of energy, and an understanding of their solar energy efficiency is used to assess the relative performance of the different materials used. Prior to this project, only reference solar cells for MJSC calibration with a maximum of three active layers were calibrated in NMIs across Europe. However, these measurements showed lower calibration reproducibility and higher uncertainties when compared with PV silicon reference solar cells. Increasing the number of junctions in MJSC, using innovative nanostructures or coupling PV with other harvesting technology such as thermoelectric (converts heat to electricity) could also increase their energy conversion efficiency to 80 %. Therefore, metrological tools are needed to support these developments, as well as new standards with lower uncertainties in energy efficiency measurements.

Scientific and technical objectives

The goal of this project was to develop a traceable metrological infrastructure to support III-V materials based MJSC. The project aimed to do this by developing techniques to enable traceable and accurate characterisation of structural, optical, electrical, optoelectronic and thermionic properties of III-V materials based MJSC, from the macro to nanoscale, in order to enhance efficiency of present devices and to enable the production of the next generation of solar cells. The project had the following scientific and technical objectives:

1. To develop methods to accurately measure electrical transport properties of III-V complex materials: band-gap, work function, dopant distribution, photocurrent, *etc*. Accurate measurements of these physical parameters are important for understanding electrical transport;
2. To characterise composition, thickness, structural and optical properties of III-V materials in order to highlight the effect of defects concentration, microstructure and interfaces on the recombination mechanisms of charge carriers;
3. To measure carrier transport between interfaces in MJSC and to characterise tunnel-junction properties;
4. To develop reliable tools to measure size dependent electronic structures of nanostructured semiconductor quantum dots;
5. To measure thermoelectric properties of III-V material and thermal transport across interfaces;
6. To develop traceable and reliable calibration methods, and standards for determining device efficiency, linearity, temperature dependence and spectral responsivity of MJSC devices.

Results

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

The determination of the electrical properties such as dopant profile, work function and electrical defects near the interface between layers requires the implementing of measurement methods, in particular at the nanoscale. This data is required to provide direct measurement of one of the main performance limitations, photocurrent – electric current as a result of solar exposure, in MJSCs. This objective was successfully completed with the following highlights:

- New facilities were developed for the nanoscale electrical characterisation of III-V samples. The successful methods implemented were: scanning Kelvin probe microscopy in air and in ultra-high vacuum, scanning spreading resistance microscopy and scanning microwave microscopy. Only a few techniques offer the possibility of measuring the electronic properties of a device in cross section with a resolution of a few nanometers and all three of the methods used by the project can measure the dopant density at the nanoscale. Characterisation of material properties layer by layer were also completed and standard operating procedures for sample preparation were developed.
- A new GaAs (gallium arsenide) reference sample was developed and used to successfully calibrate scanning microwave microscopy measurements of the electrical characterisation of III-V samples. A clear contrast between the different layers was visible and plateaus in the data corresponded well with the expected dopant densities, and were confirmed by secondary ion mass spectrometry (SIMS)

measurements. An algorithm based on three existing PV silicon reference solar cell standards was developed for III-V materials, which allows the extraction of dopant densities of semiconductor layers. The accuracy achieved was below 10 %.

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

To relate optical measurements to structural information, characterisation techniques are required and involve a combination of appropriate calibrated instrumentation. Two kinds of III-V material were considered: (i) III-V systems relevant to 3 junction solar cells and associated tunnel-junctions, and (ii) dilute nitride solar cells. Tunnel junctions are junctions through which electrons pass by a quantum tunnelling process, thus ensuring the electrical connection across consecutive junctions of MJSCs. Dilute nitrides are a group of III-V semiconductors into which dilute concentrations of nitrogen have been added, changing the performance of the material. The determination of the properties of the two kinds of material was achieved successfully with the following highlights:

- Extensive SIMS composition characterisation of III-V materials was completed and showed the level of dopant composition and the quality of the interfaces of the junction. Twelve III-V calibration samples were characterised and added to the SIMS library of data for III-V materials at project partners. This will help future quantification of dopant concentration in III-V materials. Using these new calibration samples, SIMS and grazing incidence X-ray fluorescence techniques were then compared in order to determine accurate dopant profiles.
- A joint study of the optical properties of the multilayer structures of III-V solar cell samples was completed using ellipsometry and reflectance measurements. Both are optical techniques and were used to determine the refractive indices, reflection properties and the thicknesses of the semiconductor layers. The optical methods developed can now be applied in semiconductor manufacturing to analyse the layer properties and thus to develop more efficient III-V material based MJSCs.
- The properties of a dilute nitride cell were successfully measured. As part of this innovative solar cells based on GaInAsN materials (semiconductor gallium indium arsenide with dilute nitride added) were designed, fabricated and their material properties characterised.

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

This objective aimed to better understand tunnel-junction interconnects through the design, fabrication and characterisation of tunnel junctions made with new materials lattice-matched or nearly lattice matched to GaAs (objective 1). Lattice matching is the matching of nanoscale structures within two different semiconductor materials, allowing the combined structure to exhibit properties useful in solar cells and other applications such as light emitting diodes (LED). A numerical model was designed by the project to describe electronic transport in these structures. The objective was successfully achieved and highlights included:

- New tunnel junction samples were fabricated and tested. Numerical simulations for a new design of tunnel junctions showed that a peak current up to 1300 A/cm^2 could be possible, matching the best results demonstrated prior to this project. Following this, several tunnel junction samples were fabricated by molecular beam epitaxy, and currents up to 320 A/cm^2 were measured.

- New numerical modelling was developed to better understand the electrical transport in tunnel junctions. Experimental current-voltage measurements, taken on different tunnel junction samples with a variety of doping levels, showed current peaks up to 10 A/cm^2. Using this model, extensive numerical simulations have been carried out on different types of tunnel junctions including the new tunnel junction samples. The fabrication and the modelling of this new type of tunnel junction heterostructure is of particular interest not only for reducing the electrical interconnection losses in MJSC, but also for application in the broader scientific and industrial communities that use tunnel junctions in photonics and electronics devices.

Development of reliable tools to measure size dependent electronic structures of nanostructured semiconductor quantum dots

The band-gap of the quantum dots is controlled by the size of the dots through the quantum confinement phenomenon. Quantum dots are very small semiconductor particles, only several nanometres in size, so small that their optical and electronic properties differ from those of larger particles. The band gap describes the range of energies of the particles within the semiconductor. When coupled to a conventional or MJSC cell, such a gap engineered cell could theoretically lead to a high efficiency. This objective was focused on the development of reliable tools to detect quantum dots and to determine the relationship between their size and the band-gap.

Indium Arsenide (InAs) quantum dot samples were successfully prepared by molecular beam epitaxy (a method for thin-film deposition of single crystals, widely used in the manufacture of semiconductor devices) and deposited on a GaAs substrate. Measurements using atomic force microscopy allowed the detection of quantum dots as topographic images and the density of the quantum dots and their approximate sizes were successfully determined. The electrical detection of quantum dots was done using a Resiscope system (an electrical Scanning Probe Microscope) in collaboration with the Génie électrique et électronique de Paris in Gif sur Yvette, France.

Furthermore X-ray photoelectron spectroscopy measurements and photoluminescence and cathodoluminescence measurements were performed to determine the structural properties of the quantum dots and to confirm the expected value of the quantum dot density.

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

This objective aimed to develop measurement methods to determine the thermal transport properties of complex III-V materials based MJSCs that have more than three junctions, or that use the thermoelectric effect to improve the overall efficiency of the solar cell.

This objective was achieved and a new facility to measure the thermal conductance of solar cells and wafers was developed at NPL. The results demonstrate the importance of thermal contact resistance. The impact of sample mounting and testing procedures on the precision of thermoelectric module measurement was also studied. For the first time, the variability in the electrical output due to mechanical pressure or type of thermal interface materials was quantified. Further to this, the contribution of the temperature difference and the mean temperature to the variation in the output performance was quantified. A model based on the available data for thermal conductivity of different materials was developed, and predicted that no significant thermoelectric energy recovery is possible in III-V materials based MJSC.

Development of develop traceable and reliable calibration methods, and standards for determining device efficiency, linearity, temperature dependence and spectral responsivity of MJSC devices

This objective to establish traceable and reliable laboratory calibration methods for III-V multi-junction solar cells around Europe was completed successfully and highlights include:

- A world-unique facility was developed. This facility can, for the first time ever, calibrate MJSCs, without the need for the expensive hot-air balloon flight currently used to carry the cells to high altitude for calibration. A set of synthetic calibration methods for MJSCs (using terrestrial means) was developed with an uncertainty close to 0.5 %, which is comparable to the measurement uncertainties achievable during hot-air balloon flights in existing calibration methods.
- Experiments on MJSC and component cells were completed and following a reduction in calibration uncertainty in component cells, a photocurrent linearity evaluation was performed. The project demonstrated that the electrical response (or photocurrent) of a MJSC component cell is linearly related to the amount of solar radiation falling onto it. The temperature dependence of the open circuit voltage, which is the difference of electrical potential between two terminals of the cell when disconnected from any circuit, in MJSC was also successfully determined. A reflectance setup was modified for use with component cells and MJSC, and a setup to measure the response of the cells at different wavelengths was developed and validated.
- Synthetic calibration facilities for component cells and whole MJSC were established and successfully

compared with existing calibration facilities. Unified calibration procedures and measurement uncertainty budgets were derived from the experiments undertaken and were included in the project's good practice guide on multi junction reference solar cell calibration methods. Angular, temperature and spectrally dependant characterisation studies were also completed on MJSC devices and the suitability of an LED based Solar Simulator for quadruple-junction MJSC calibrations was proven.

Actual and potential impact

This project established the measurement infrastructure required by European industries and research laboratories to accelerate the development and adoption of next generation multi-junction solar cells with the aim at increasing the solar cell efficiency to 50% or higher.

Dissemination

A stakeholder committee, formed of industrial partners (e.g. Alstom, Surrey Satellite, Thales and Bruker) from the photovoltaic and semiconductor industries, closely followed the project as it developed. They endorsed the importance of the results of the project and, within the next five years, plan to use the standards calibrated by partners of this project with the synthetic methods (using terrestrial means) developed in the project.

The project was presented in numerous high profile international conferences including The Conference on Precision Electromagnetic Measurements (CPEM) in Rio and Ottawa, the European PV Solar Energy Conference and Exhibition (EPVSEC) in Hamburg and Munich, spring meetings for the European Materials Research Society (E-MRS) in Lille and Strasbourg and the International Conference on New Developments & Applications in Optical Radiometry (NEWRAD) in Tokyo.

14 papers were published in peer reviewed journals such as IEEE Journal of Photovoltaics, Applied Physics Letters and Measurement Science Technology. Three articles were published in magazines e.g. PTB news and METinfo.

Training events delivered during the project included:

- Five training courses and workshops for external audiences, dealing with the metrology for energy harvesting, a spectroradiometer and broadband intercomparison campaign, MJSC calibration methods, and highlights from this project.
- An e-learning training module on nanoscale characterisation: "New SMM Applications for Semiconductors & Buried Structures, 2D Materials, and Living Cells in Buffer Solution". This e-module is available on the project website.
- Training courses for the consortium on high frequency measurements and scanning microwave

Early impact

Three European organisations have demonstrated their interest in the synthetic calibration method for MJSCs developed in the project and have stated:

- "AZUR SPACE plans to utilise standards which are synthetically calibrated with the methods developed in this project within their metrology department";
- "The achieved reduction in measurement uncertainty of component solar cells can directly improve the metrology at AIRBUS D&S";
- ESA Document - Comparison of primary (balloon flight) and synthetic calibration of solar cells – p18. June 2015: "one can expect an overall uncertainty of synthetic methods of around 0.6% [...] which is then even slightly lower compared to the uncertainty quoted for the balloon calibration by CNES."

In addition:

- The project partners have already helped one end user, the Finnish solar simulator manufacturer Endeas Oy, to solve issues in uniformity measurements.

- The high gain transimpedance amplifier developed in this project to characterize optical properties of III-V materials through the measurement of photo detector currents is now commercially available from the company Hasseb in Finland (objective 1).
- SOITEC, CEA and Fraunhofer-ISE have recently announced a new world record for solar cell efficiency. Discussion is well underway between NPL, LNE and SOITEC for collaborative work aiming to provide these four-junction solar cells fabricated by stacking two dual-junction systems.

Two good practice guides were also written, and distributed to partners and stakeholders and are available on a specific exchange platform dedicated to the JRP:

- A good practice guide on calibration procedures for multi-junction solar cells
- A good practice guide addressing best methodologies and protocols for measuring structural, electrical, optical and thermal transport properties of complex III-V structures

Contribution to standards

The project contributed to changes in the draft standard IEC 60904-8-1, Measurement of spectral responsivity of multi-junction photovoltaic devices. The standard was published in May 2017.

A report on electrical Scanning Probe Microscopy based measurements carried out in the project was also sent to the secretary of IEC TC-113 (Nanotechnology for electrotechnical products and systems) and is available to the ISO TC 229 Nanotechnologies committee.

Potential future impact

The project has contributed to better understanding of key III-V semiconductor transport properties in complex heterostructures, with particular respect to nanostructured material. The close collaboration within the consortium will continue on the metrology for electrical scanning probe microscopy and calibration activities related to MJSCs. The technical reports and data resulting from the project are available to industry and academia across Europe, and will feed into standards bodies for even wider dissemination.

List of publications

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