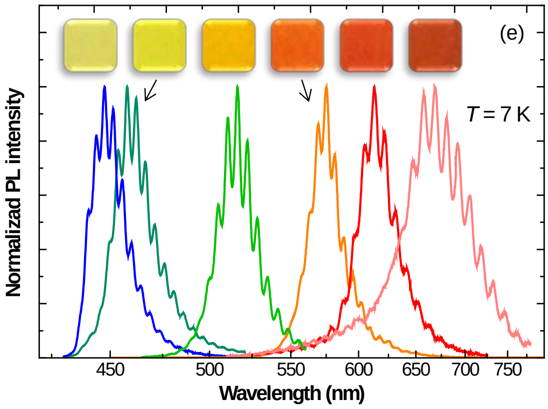
FINAL REPORT

Currently, the photovoltaic (PV) market is dominated by single-junction crystalline silicon modules because of their low cost and long-term reliability. However, higher conversion efficiencies are obtained using advanced multi-junction techniques operating under concentration. In this context, the target of this project is the development of a new generation of indium gallium nitride (InGaN) on silicon solar cells exploiting the bandgap engineering capabilities of InGaN alloys, which should drive III-nitride PV devices to unprecedented performance in terms of (i) covering the full solar spectral range, (ii) stability under concentration conditions / in harsh environments, (iii) compatibility with the already existent silicon technology and (iv) conversion efficiency. The project faced a number of technological challenges: new state-of-the-art for nitride material design, and growth and fabrication technology adapted to the InGaN specificities. We proposed a completely new approach to the nitride-based solar cells, addressing directly nitrogen-polar high-In content layers on low-cost silicon substrates. In addition to CEA-Grenoble, INAC/SP2M/NPSC, the team also included researchers from CEA-LITEN and CNRS-Institut Néel.

The research has evolved from basic studies of single InGaN-on-silicon layers to the fabrication and complete characterization of full devices integrating InGaN in the *p*-doped region.

In terms of ***material growth***, the Researcher has focused on the growth by plasma-assisted molecular beam epitaxy, since it is currently the best technique to implement high quality InGaN films with high In mole fraction (>25%). The InGaN structures were deposited on gallium nitride (GaN) on sapphire templates, and this technology should be subsequently transferred to silicon substrates. We have reported the <u>interplay between In incorporation and strain relaxation kinetics</u> in thick InGaN (30% of In) layers.[1] This is relevant for the synthesis of high-In-content quantum wells or thin films in the active region of emitters and detectors, since their thickness and composition depend not only on the growth conditions, but also on the strain state imposed by the underlayers. Regarding ***micro-fabrication***, the main challenges, associated to the implementation of a *p*-contact structure which fits the compromise between transparency and carrier collection, and adapted to the roughness and conductivity of the *p*-(In)GaN layer, were overcome by the development of a <u>double *p*-contact design</u> based on a Ni/Au technology.



Photoluminescence emission of InGaN films (16-42% In), covering the whole visible spectrum. Top: photograph of the samples.

Below a ***summary of the work carried out towards the objectives*** of the project is presented.

* *<u>Control of the InGaN on silicon interface</u>*

The integration of a junction (J) on a silicon substrate needs from minimizing the defect density and the resistance at the interface. The band alignment between silicon and InGaN seems theoretically favourable, but there are some challenges from the growth point of view, such as the silicon and In interdiffusion at the interface and the control of the polarity. Also, nitrogen polarity is preferable in solar cells containing In-rich active regions to prevent carrier collection barriers at the *n-i* interface due to polarization issues. During this project the Researcher has achieved the successfully synthesis of thick InGaN films on silicon with a 3D nanocolumn-like conductive InGaN interface buffer layer, controlled and homogeneous nitrogen polarity, good structural quality and the desired In mole fraction (16-42%).[2]

* *<u>P-type doping and conductivity in InGaN material</u>*

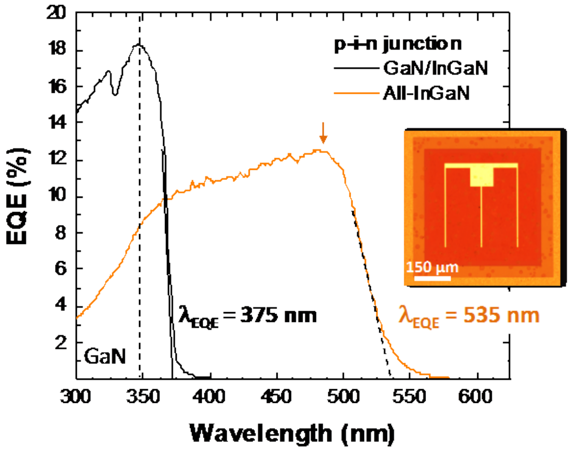
In a solar cell, the upper layer (with the same or larger band gap energy) must be *p*-doped, and its conductivity should be as low as possible to reduce recombination losses associated to the access resistance. We have large experience in *p*-type doping of GaN. However, high-In content InGaN sets an additional challenge due to its strong tendency to be *n*-type doped and its high electron affinity, making difficult to implement a *p*-type contact structure. The Researcher has assessed these problems by exploring the incorporation of the Mg dopant in InGaN (30% In). The evaluation of the doping levels

[1] S. Valdueza-Felip et al. J. Appl. Phys 116, 233504 (2014)
[2] S. Valdueza-Felip et al. To be submitted (2015)

points to a hole concentration of 1-2×10^{19} cm^{-3} at low Mg temperatures. The structural quality of the layers improves strongly (number of stacking faults decreases). However, an inversion of polarity and doping type is observed in presence of Mg. Investigations about their origin are underway.

* *Heterojunction vs homojunction InGaN solar cells*

With the collected information we have fabricated *n-i-p* InGaN hetero and homojunctions to evaluate the best device strategy. Junctions were grown on various substrates, including silicon using the conductive 3D InGaN buffer layer previously developed and on strained-engineered GaN-on-Si. On each substrate, *n-i-p* junctions were fabricated using different *p*-layers, namely (i) *p*-GaN, (ii) graded *p*-InGaN (0-35% In), and (iii) *p*-InGaN (35% In). Samples were mesa-structured and contacted using the double Ni/Au (*p*-side), and Ti/Al/Ni/Au (*n*-side).



EQE of InGaN-based solar cells. Right: top microscope photograph of the device.

All devices show rectifying current density vs voltage behaviour. However, in GaN-terminated structures the low photocurrent extracted from the InGaN layer is attributed to a deficient hole collection from coming from the *p-i* interface because of polarization issues. On the contrary, InGaN homojunctions present a flat spectral response in the blue-green spectral region with a sharp cut-off red shifted to 535 nm and a peak external quantum efficiency (EQE) of 12.5% at 480 nm, as expected from the band diagram alignement.[3]

Added-value to the Project: Improving as-grown InGaN/GaN solar cells

During the duration of the project, the Researcher has been working simultaneously on the fabrication of solar cells based on InGaN/GaN multiple quantum wells (MQW) grown by metalorganic chemical vapour deposition. The research was focused on the optimization of the MQW active region design, such as QW/barrier/total thickness and In composition, to improve the device performance.[4] Conversion efficiencies of as-grown structures up to 2% were achieved without any post-treatment. Although such values are not commercial, there is a huge interest in developing these structures to integrate them with non III-nitride multiple-junction PV devices and optimize their power conversion yield in the UV region.

Socio-economic potential impact

Europe is currently one of the major actors in photonics within harsh worldwide competition with Asian and US R&D. Europe leadership depends on its capacity to develop innovative components and systems, and to integrate these into products across all sectors. Indeed, to keep Europe's industry and R&D and innovation on the leading edge, younger generations have to get involved in fundamental research breakthroughs and master the emerging technologies. Solar energy is a a green, safe and highly reliable solution to overcome current problems, so the development of high-efficiency PV panels is an extremely important topic. Lately, efforts have been strongly devoted to the research of nitride solar cells at global level. InGaN based PV devices show promising predicted efficiencies of aprox. 62% for a full spectrum 4J InGaN cell, 56% for an InGaN (1.75 eV) junction on top of a 3J GaAs-based cell, 36% for an InGaN(1.8-2 eV)-on-silicon 2J cell, and 21% for a single InGaN (1.45 eV) homojunction.

Along these lines, the **SolarIn** project offers an European contribution of huge importance for the implementation of these new generation of high-performance solar cells, with direct applications in critical fields like: PV in buildings, electric fences, remote lighting systems, telecommunications and remote monitoring systems, solar powered water pumps, rural electrification, water treatment systems, space and solar powered vehicles; applications which have become more common and useful than ever before thanks to the newer solar solutions on the market today. Actually, progress in PVs keeps revolutionizing our daily. For more information about the Marie-Curie project IEF#331745 **SolarIn "Solar cells based on InGaN nanostructures on silicon"**, please follow the SolarIn website or contact the Researcher Sirona Valdueza-Felip. See you soon!

[3] S. Valdueza-Felip et al. To be submitted (2015)

[4] S. Valdueza-Felip et al. Jpn. J. Appl. Phys. 52, 08JH05 (2013); Appl. Phys. Express 7, 032301 (2014); Semic. Today, in press the 25th March 2014; Submitted to Appl. Phys. Lett. (2015). L. Redaelli et al. Appl. Phys. Lett. 105, 131105 (2014); Submitted to Jpn. J. Appl. Phys. (2015)