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# Strain relaxation of In-rich InGaN layers for full-spectrum micro-LED displays

## *InGaN-Full-Spectrum*

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### *ABSTRACT*

A semiconductor bandgap can be tuned by straining. We used an original way for deforming large scale macroscopic thick membranes. Stiff semiconductor membranes were strained by soft siloxane slabs. While elastically straining the structure, an operando spectroscopy probed the deformation through Raman scattering and x-ray diffraction. Micrometre-thick silicon membranes were strained biaxially over millimetric surfaces towards their ultimate tensile strength. Such strain levels in III-N semiconductor compounds allow extending nitride LED emission over the entire visible spectrum. As a breakthrough after decades-old research, we unlocked the synthesis of monocrystalline films with a cell parameter tailored to values unavailable in nature.

*Keywords: Strain; bandgap engineering; epitaxy; nitride; LED; screen; full-spectrum emission.*

## 1. INTRODUCTION

Strain highly affects fundamental physical properties of semiconductors with potential significant benefits at the device level [1]. External strain modifies the electronic band structure in a way that can entail fundamental parameters such as carrier mobility [2], band gap energy, potentially toward a transition type from indirect to direct bandgap [3]. Inorganic semiconductors, as fragile materials, tolerate only small linear strain before breakage. Now, thanks to their high sensitivity, relatively low strain can tune their properties. A new potential resides in the ability to strain macroscopic surface membranes in the order of 1% or more. The highest strain levels can be reached in specific nanostructure geometries such as nanowires [4] or 2D materials [5]. But methods for straining are either incompatible with mass production or provide strain levels far below the theoretical elastic limits of materials. Our project aimed at closing this “strain gap”.

Strain engineering for nitride materials based heterostructures is key in the field of InGaN based light emitting diodes (LEDs). The technique of heteroepitaxy can provide strain but due to principles related to thermodynamics and growth kinetics, this technique cannot achieve by itself strain levels sufficient for reaching red wavelength emission in planar technology. An innovation at the substrate level is needed. Using only materials and process steps from the semiconductor industry, we have established a generic method for tuning the lattice parameter of any material shaped under the geometry of thin membranes to be bonded on host substrates. Furthermore, we have invented and built a tool allowing operando investigation while achieving the target strain. This allows the online tuning of the correlated optoelectronic properties of a material. When combining epitaxial strain, external strain and chemical composition tuning by re-epitaxy, this method extrapolated to InGaN will allow synthesizing monocrystalline layers at unprecedented indium content for shifting the emission wavelength all along the visible spectrum.

Using silicon as a calibration material possessing similar mechanical properties as InGaN compounds, we have developed a straining process that allowed us to observe and control the elastic deformation of a semiconductor material up to the record tensile strain value of 1.8 % (biaxially).

*(The detailed work concerning the fabrication of InGaN membranes cannot be disclosed here for reasons of confidentiality. Patent under filing process.)*

## 2. STATE OF THE ART

Straining on large surfaces usually proceeds with thin films epitaxy mismatched to the substrate. The maximum thickness above which a sudden relaxation is observed for a given mismatch depends the materials system. Epitaxy for the silicon-germanium material system, as an example, cannot strain µm-thick layers. This critical (relaxation) thickness for a biaxial strain around 1% remains under 10 nm [13]. Such thin layers are not suited for processing optical devices typically requiring layers 1 to 2 µm-thick. Tensile strain in such semiconductor membranes is supposed to shift the bandgap to a direct bandgap and increases its electron mobility for the case of Si/Ge [2,4,6].

In this field the absence of substrate with a lattice-matched parameter for nitride emitters has been clearly identified as the technology roadblock. In the material system of InGaN, a seed layer is needed for tuning the lattice parameter of the epistructure containing multi-quantum wells. This will allow producing LEDs over the full visible spectrum [7] (see Tab. 1).

### BREAKTHROUGH CHARACTER OF THE PROJECT

Although different methods have been reported to impose strain to semiconductor membranes and nanostructures, no scalable process exists allowing both a full control and a fine tuning of the strain level applicable to wafer scale membranes. Fine tuning of strain at low strain levels has been achieved in some areas, such as ferroelectric oxides, by a fine tuning of the lattice parameter of the substrate by its chemistry. But such fine tuning on the substrate side is not possible for common semiconductors and even for ferroelectrics it cannot be considered compatible with mass production. Our proposed process addresses the controlled straining of membranes out of rigid/brittle materials and has the strong advantage of:

- overcoming the low strain limit met by epitaxial processes.
- allowing fine tuning of strain at low or high levels in systems where fine tuning of the lattice parameter on the substrate side is impossible.

These two points are the key roadblocks for full spectrum application of InGaN LEDs. Our method offers further application to wafer scale membrane sizes and transposability to any material system as well as easy process integration as it is using only materials and polymers already used in the context of semiconductor processing.

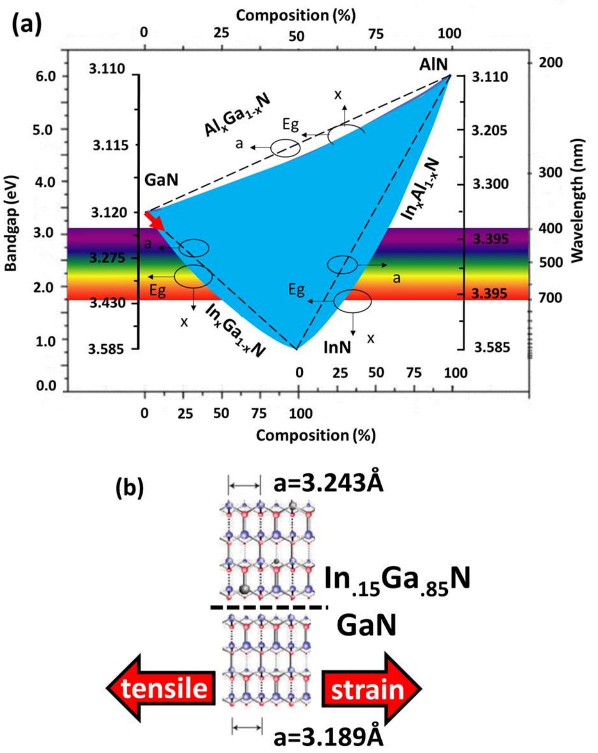

**Fig. 1**. (a) The bandgap versus the lattice parameter for InGaN, AlGaN and InAlN using bowing parameters (after [8]). (b) The figure summarizes the goal of our project to offer a a fully relaxed pseudo-substrate for the epitaxy of $In_{0.15}Ga_{0.85}N$.

We do further insist on the optimisation of our process for material thicknesses in the range of 0.2 to 2 µm. A thickness regime typically required for devices and typically not suitable for the imposition of homogeneous strain by epitaxial means.

**Tab. 1.** Representatives examples of technical targets related to lateral lattice variation (strain or relaxation) as business cases from the industry.

| Material / Appli-cation | Max strain/ relaxation available today | Required (motivation) | PolyStretch® (our work) |
|---|---|---|---|
| **Si** | 0.4% (epitaxy) | 2% tensile strained-Si bonded to Si substrate (fully relaxed SiGe50% equivalent) | 1.8% strained-Si obtained (100 nm-tick) |
| **SiGe** | 0.4% (epitaxy) | fully relaxed SiGe70% bonded to Si substrate | achievable from Ge substrate |
| **InGaN/ GaN** | +0.66% from GaN cell parameter (relaxation) | up to +1.9% from GaN cell parameter (epitaxial pseudo-substrate) | achievable from InGaN/GaN epilayer |

## 3. PROJECT RESULTS

The core result of the project is the establishment of a method for imposition of elastic strain in rigid semiconductor membranes in a controlled and homogeneous manner up to values of ultimate tensile strain. This allows the following:

- imposing significant changes to the electronic properties of semiconductors without changing their chemistry, allowing thus the exploitation of existing foundries and their production lines (heavily relying on established processes) that are usually incompatible with changes in chemistry (resource efficiency).
- supplying new substrate materials with lattice parameter match.

We have developed a scalable process that allows imposing tuneable strain levels to rigid membranes bonded on thick polydimethylsiloxane (PDMS) slabs. Application of an easy to control external force leads to an elastic tensile biaxial expansion of the bonded rigid layer. The materials of interest in our project are InGaN alloys. A variation of the lattice parameter in the 1 % range in these materials would allow to exploit so far inaccessible InGaN alloys with epitaxial match to produce highest efficiency nitride LEDs for the complete visible spectrum. Our process produces such lattice parameter variation by pure mechanical deformation of a previously grown layer. It allows thus to vary the lattice parameter independent of chemistry. The results presented in this article are obtained with Si. Si and InGaN alloys have similar mechanical properties, with InGaN alloys possessing about twice the elastic strength than Si. Both material classes are amongst the hardest materials commonly used in microelectronics and are usually perceived as "brittle" due to their tendency of shattering when mechanically shocked. This turns out not to be true when thin layers of such materials are supported by soft polymers. With a well-controlled bonding procedure, such rigid layers can be elastically expanded to levels that largely overcome the limits imposed by epitaxy, both in terms of strain amplitude and layer thickness. Si has the advantage of being commercially available in the form of membranes of reproducible quality. Together with its mechanical proximity to InGaN it represents thus an ideal material for process developments that are mainly optimizing the mechanical handling, bonding, and the polymer environment of the rigid membrane. The overall process developed here is thus blind to the chemical nature of the rigid membrane but rather sensitive to its elastic properties. The main results obtained in our straining apparatus are presented in Fig. 2. The data in Fig. 2(a) show the evolution of the Raman shift for a 0.1 µm-thick Si membrane for increasing elastic expansion. The observed shift of the Raman response corresponds to a biaxial elastic strain of 1.8 %, a world record level for Si membranes. A similar measurement series is shown for 1.0 µm-thick Si membrane in Fig. 2 (b) for biaxial expansion of up to 0.5 % in four steps, showing the good control of fine tuning of lattice parameters with this tool. The same control of biaxial expansion has been measured by x-ray diffraction as presented in Fig. 3.

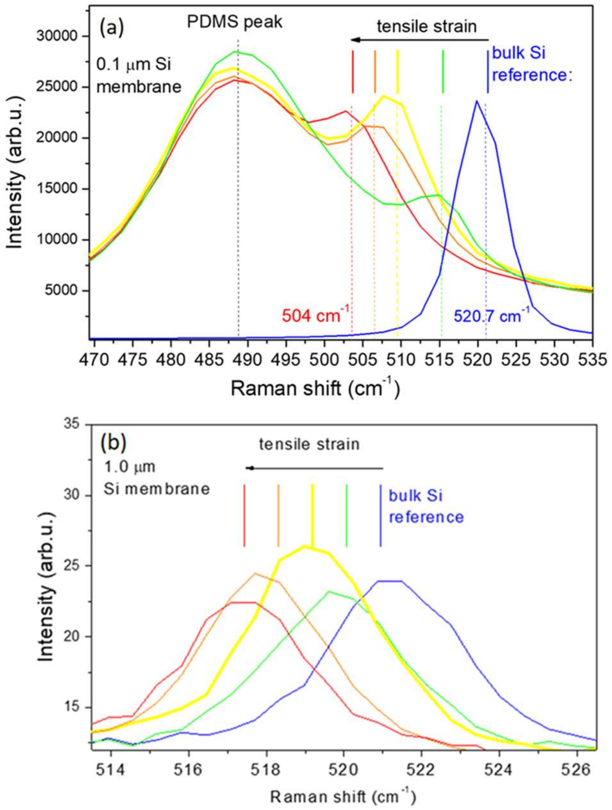

**Fig. 2** (a) Raman shift measured from a 0.1 µm-thick Si membrane bonded to PDMS under tensile strain (blue line for the bulk Si shift given as a relaxation reference). The Raman signal from the PDMS dominating the spectra can serve as a second calibration. The evolution of the Si peak reaches its maximum at 504 cm$^{-1}$, corresponding to tensile biaxial strain of 1.8 %. Note that the thin Si layer presented an initial strain while mounted in our apparatus. (b) Raman shift measured on a 1 µm-thick Si membrane. The biaxial tensile strain can be incrementally controlled up to a Raman shift of around 4 cm$^{-1}$.

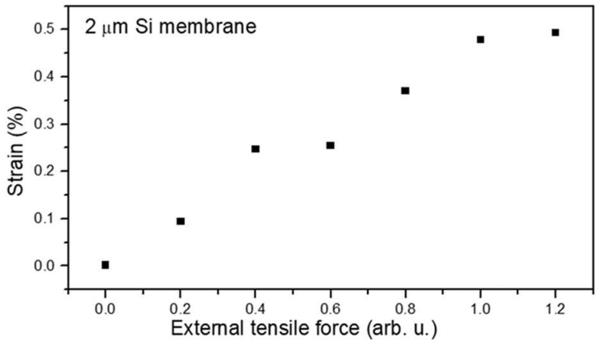

**Fig. 3:** X-ray diffraction monitoring of evolution of biaxial tensile strain in a 2 µm-thick Si membrane, showing the well-controlled linear relationship between external force and lattice parameter.

We emphasize that our methods impose ultimately high tensile strain in rigid membranes even of thickness levels relevant for devices.

**Tab. 2.** Example of lattice values and lattice variations representative for shifting light wavelengths toward the red for InGaN LEDs. A tension applied on GaN equivalent the one obtained on Si (1.8%) allows a relaxed re-epitaxy of InGaN 15% for full colour red-green-blue emission.

| Indium content (%) | 0 (GaN template / reference) | 7.5% | 15% |
|---|---|---|---|
| *InGaN relaxed lateral lattice (Å)* | 3.184 | 3.214 | 3.244 |
| *relative lateral tension (%)* | 0 | 0.94% | 1.89% |

## 4. FUTURE PROJECT VISION

A project selection to Attract Phase 2 would allow transforming our prototype toward a small production within an industrial environment along all technology readiness levels (TRL).

### 4.1. Technology Scaling

The strength of our innovation resides in the simplicity of a well matured original concept. We interconnected usually separated physics and chemistry engineering fields. We developed simple, reliable, and low-cost technology building bricks based on industrial raw materials compatible with large volume manufacturing. In this respect, the technology has been developed since day one for allowing a straightforward scaling concerning the technical side.

To demonstrate the technology in a relevant industrial environment, we plan building strain-engineered wafers in small series. Before this, we need to fine-tune the process for selecting the best option among variant ones. A small dedicated team of 3 persons will be hired. And in terms of facilities, we benefit from all the necessary equipment and expertise in Grenoble campus for research and engineering (ESRF, CNRS, CEA-LETI, University, clean-rooms, industries, professional networking associations, etc.).

Several process tools have already been built and we plan to have their fabrication industrialised with the support of a world-class company specialised in bonding. Also, we will use facilities and clean-rooms based on the CEA-LETI campus. We will benefit from the industrial network at Grenoble continually active in the field of engineered semiconductor substrates and optoelectronic devices (Soitec, STMicroelectronics, Lynred, Thales/Trixell, etc.) for climbing all steps of the TRL scale up to production. In three years, our development will attain the maturity of an industrial product.

### 4.2. Project Synergies and Outreach

During Attract Phase 1, two research and technology centres have teamed up with us: (1) the CEA-LETI (Grenoble) for its expertise in epitaxial growth and LED technology; (2) IKZ (Berlin) for crystal defect theory and characterisation. A third research and technology centre agrees to partner within Attract Phase 2: the Institut des Mines-Télécoms (IMT) in Lille-Douai (France) for composite structure and solid mechanics modelling. The SME SET Corporation SA would also agree to be part of our Consortium.

Among the different funded projects, based on technical goals and profiles, we did not identify any potential partner to cluster with.

### 4.3. Technology application and demonstration cases

Strain can present even more eminent effects in perovskite structure materials on the physical structure or morphology of crystals with phase changes. Spectacular behaviours have been observed like the appearance of ferroelectricity [9] and ferromagnetism [10].

Several researchers at the European Synchrotron and in our scientific and engineering network are candidates for testing our method for various materials. We envision new developments in semiconductors that could be applied in the mid-term. Large strain applied to perovskite materials can even produce phase changes inducing fundamental phenomena such as ferroelectricity [5].

We plan to create a scientific and technical community/consortium around strain engineering. The ID01 beamline led by Dr Schülli, co-author here, specializes in strain engineering measurement for academia and industrial customers. The discussions between Nelumbo Digital and the ESRF have started for the ignition of such an organisation about strain engineering.

Nitride materials present a bright future with their expected adoption in many screen markets. Among screen markets, the most appealing should be the erupting market of augmented reality. A critical parameter for this application such as the response time shows to be one thousand times better. And almost every parameter shows a performance far above technological competition (luminous efficacy, luminance, contrast, power consumption) [11]. But a remaining drawback of today’s nitride technology before its adoption concerns the necessary co-integration of LEDs from different semiconductor types: nitride large bandgap *vs.* arsenide low bandgap. This co-integration requires an incredibly challenging pick-and-place method, seemingly impossible to adapt to 10µm-pitch augmented reality screens up to now [12]. Our project during Attract Phase 2 will produce a 3-colour LED assembly on the same substrate, a game changer for the whole screen industry.

### 4.4. Technology commercialization

The commercial need for a bandgap engineered solution is highly validated by the market. The innovation we have in hands can be considered as both techno-push and market-driven.

We have a direct commercial contact with a world leader for the fabrication of virtual reality screens with a division based in Europe. In a concrete way, our plan is to convince this company to become an alpha-customer. We would provide him insight supporting his own technology development in the goal of getting ahead of his competition by using our technology. This will be governed by non-disclosure agreements and time-limited exclusivity.

We have also discussed with private investors interested in working with us. We are expecting a first commercial arrangement after initiating a contract with the alpha-customer.

### 4.5. Envisioned risks

Such a competitive domain underlines substitutive technologies for investments as the main economic risk. We evaluate the technological risk as extremely low as we did not identify any difficult step all along the process under development. All basic operations present a high certainty for a final success.

### 4.6. Liaison with Student Teams and and Socio-Economic Study

Managing students on short internships periods was difficult during Attract Phase 1 because of our low availability. In addition, projects intended to be marketed require secrecy before protecting the intellectual property. Attract Phase 2 would allow a totally different approach. The hired team would have time and high interest for supporting students bringing their additional workforce and creativity.

## 5. ACKNOWLEDGEMENT

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