Trap mediated electromechanical properties of silicon nanostructures

I. Contexte, positionnement et objectif(s) de la proposition

The electromechanical properties, and in particular the piezoresistance (PZR), of bottom-up silicon nanostructures differ fundamentally from those of bulk silicon[1]. A poor understanding of the microscopic mechanism underlying this effect stands in the way of the development of nanoscale device and sensor applications that exploit the phenomenon. **TRAMP**'s principal objective is to quantitatively describe this anomalous PZR. Specifically, the validity of the piezopinch model based on stress-induced changes to the activation energy of chemically induced electronic defects[2] will be tested on scalable, top-down silicon nanostructures before demonstrating a prototype strain gauge sensor based on an adapted M&NEMS concept[3]. The intermediate objectives of **TRAMP** are therefore to:

- fabricate electrically connected, mechanically released top-down silicon nano-objects (< 300 nm) tailored to specific scientific experiments (necessitating rapid prototyping and turn-around, and multiple short production runs, an area of expertise at **IEMN**); chemically induce electronic defects in these objects and measure PZR and the Hall effect on them under applied stress (**PMC**).
- adapt and use a combination of micro-Raman and tip enhanced Raman imaging to locally map mechanical stress *in operando* in individual top-down silicon nano-objects (**LPICM**).
- use temperature dependent trap spectroscopy[4] adapted to individual nano-objects to *in situ* identify and characterize electromechanically active defects (**PMC** with U. Melbourne).
- develop a quantitative model of the anomalous PZR in silicon nano-objects (**PMC**).
- evaluate (in light of initial **TRAMP** results) opportunities for novel devices exploiting the anomalous PZR via the modification of a near commercial prototype accelerometer (**LETI**).

The **TRAMP** partners recently undertook a collaborative, experimental research effort[5] which clearly identified anomalous PZR in chemically treated, *p*-type silicon nanomembranes whose sign is opposite to that of the bulk effect, and whose magnitude is approximately 20 times larger (see Fig. 1). In contrast to other reports on bottom-up objects[1], the measurements are made on top-down nanomembranes and are stable even under ambient conditions. The unambiguous nature of the observations is important in the context of the debate (in which the **TRAMP** partners have played a central role[6]) about the veracity of anomalous PZR in silicon nano-objects. The anomalous PZR is observed after exposure to concentrated HF. In addition to creating deep hydrogen related traps in silicon[7], HF neutralizes the acceptors thereby partially depleting the samples and significantly increasing their resistance. In this limit, the resistance is sensitive to the charge state of electronic defects, suggesting a possible role for electro-mechanically active defects in the anomalous PZR. The anomalous PZR would then arise from a stress-induced change to the free carrier concentration[2] which contrasts with the stress-induced mobility change of the usual bulk PZR[8].

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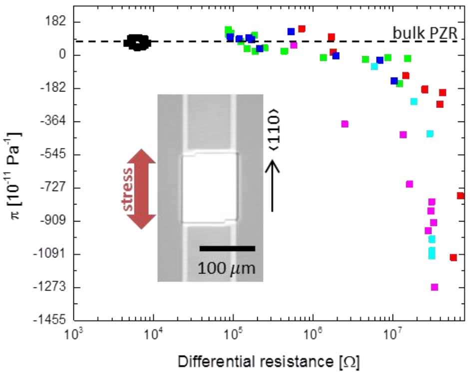

Fig. 1: PZR π-coefficient measured in 300 nm thick, *p*-type (Boron) silicon nanomembranes (unpublished). The inset image shows a nanomembrane (white area) with Ohmic contacts (light grey) that permit a resistance measurement along the ‹110› crystal direction. A tensile stress of approximately 10 MPa is applied, as shown, parallel to this direction. The known, bulk PZR of *p*-type silicon in this direction ($\pi \cong 70 \times 10^{-11}$ Pa^{-1}) is measured in the as-fabricated nanomembranes (black squares) for which $p = 10^{18}$ cm^{-3}. A subsequent concentrated HF treatment partially neutralizes the Boron acceptors, resulting in a non-linear IV characteristic (not shown) and significantly increased values of the differential resistance (coloured squares). At the highest values of differential resistance the PZR has an anomalous sign and is significantly larger than the bulk value, with π-coefficients approaching -1300 x 10^{-11} Pa^{-1}. The nanomembrane is still p-type in this regime, suggesting a non-bulk origin of the PZR, postulated to be linked to electromechanical activity of defect states.

In terms of risks, the existence of the anomalous PZR is not in question, and Fig. 1 with its caption is included to prove this. Trap spectroscopy (I-DLTS[4]) may not reveal any obvious electromechanical activity of defect states or Hall measurements may reveal that it is principally the mobility (and not the carrier concentration) which depends on stress. Although such observations do not imply a bulk PZR, they would bring into question the defect based interpretation of the anomalous PZR. An alternative model will then need to be developed but this is a risk associated with the accepted scientific process. If the piezopinch model is however validated by experiment, a risk associated with the eventual use of the anomalous PZR in a device will be its possible temperature sensitivity. I-DLTS requires temperature dependent measurements of sample conductance to be made, so the apparatus adapted to this will also be used to evaluate the temperature coefficients of resistance and of the PZR π-coefficient, both of which are important parameters in a device specification.

II. Organisation du projet et moyens mis en œuvre

The **TRAMP** partners are:

The Laboratoire de Physique de la Matière Condensée UMR7643 CNRS/Ecole Polytechnique (**PMC**)

Expertise: the physics and chemical modification of semiconductor nano-objects.

Coordinator: Alistair Rowe previously led 3 ANR funded projects including two on PZR in nanostructures, is a joint holder of 3 patents on piezoresistive sensors with **IEMN**, has a 10 year record of PZR publications in high impact physics journals. Currently coordinator of a CNRS funded project (10k€) undertaking DLTS studies of stressed defects with Prof. Jeff McCallum's group[9] at the University of Melbourne. Ph.D. supervisor of Heng Li (funded 1st year Ph.D.). Other members: F. Ozanam, P. Allongue, A. Wack, D. Lenoir

Related work: in this document see Refs. 2, 5, 6, 8 and 9.

Funding required: 1 year post-doc salary (50 k€), closed cycle cryostat with heating option (50 k€), consumables (30 k€), laboratory equipment (20 k€) travel/communication costs (20 k€). Total: 170 k€.

Institute d'Electronique, de Microélectronique et de Nanotechnologie, CNRS/University of Lille (**IEMN**)

Expertise: rapid prototyping and turn around silicon nano-object fabrication. TRL1 to TRL3 range.

Personnel: S. Arscott (lead), F. Vaurette, G. Curley, M. Dewitte, A. Fattiorni and L. Fugère

Related work: in this document see Refs. 5, 6 and 8.

Funding required: nanofabrication costs (90 k€), licenses (10 k€), consumables such as SOI substrates (15 k€), travel and communication (15 k€). Total: 130 k€

Laboratoire de Physique d'Interfaces et Couches Minces, UMR 7647 CNRS/Ecole Polytechnique (**LPICM**)

Expertise: micro- and nano-Raman imaging.

Personnel: R.Ossikovski (lead) and E. Garcia-Caurel

Related work: in this document see Refs. 5.

Funding required: 1 year post-doc salary (50 k€), equipment costs (40 k€), consumables (20 k€) and travel/communication costs (10 k€). Total: 120 k€

[9] B.C. Johnson, **J.C. McCallum**, L.W. van Beveren and E. Gauja, Thin Solid Films **518**, 2524 (2010)

C.E.A. LETI (**LETI**)
Expertise: production line fabrication and tech. transfer of silicon NEMS with integrated PZR detection, and large scale microelectronic device fabrication (TRL3-TRL7).
Personnel: S. Hentz (lead), G. Jourdan, M. Gely
Related work: in this document see Refs. 3.
Funding required: Two 52 step 200 mm wafer processes (80k€), equip./consumables (20k€). Total: 100 k€

III. Impact et retombées du projet

The electro-mechanical properties of bulk silicon are widely exploited in sensors in a range of commercially available products, from accelerometers in smartphones to pressure sensors for the medical and automotive markets[10]. Indeed **LETI** is working on such devices that are close to industrial transfer[11]. While these sectors currently represent only 1 % of global semiconductor sales, forecasts[12] suggest that data collection via sensors in connected devices (the so-called Internet-of-Things[13]) will be the major growth driver over the next decade. At the same time the main sales areas for semiconductors – logic and memory devices – exploit the PZR[14] and trending towards devices in the nanometer size range[15]. In light of this an obvious and interesting question is **'will the electromechanical properties of semiconductor devices and sensors fundamentally change at the nanoscale and if so, how?'**. Preliminary work to this project (see Fig. 1) suggests that the answer to this question is 'yes', and the objectives of **TRAMP** might be characterized as a step towards the 'how'. Knowledge of the 'how' is essential, either to ensure that future devices behave in a known, predictable way, or with a view to novel device applications[16] not possible with bulk material.

The nano-objects studied during **TRAMP** will be fabricated from ultra-thin SOI using an integrable, scalable top-down process[3] – this is an important advantage of the technical approach proposed here when compared with existing work on bottom-up nano-objects[1]. The eventual impact of **TRAMP**, in terms of sensor and device potential, will however depend crucially on the ability to render desirable defect states stable as a function of time. Initial characterization of for example, the temperature sensitivity of prototype strain gauge based devices made at **LETI**[3], will be undertaken in the latter stages of the project.

During **TRAMP** state-of-the-art instrumentation will be adapted and used to characterize the electro-mechanical properties of individual nano-objects, specifically micro-Raman spectroscopy and TERS, along with admittance spectroscopy techniques such as I-DLTS[4]. In the former case, the instrumentation is applicable to the characterization of the optical and mechanical properties of a range of nano-objects, while the latter is applicable to electrically connected nano-objects. The proof-of-concept use of these techniques on silicon nano-objects will open up possibilities for the characterization of other nanostructures which may in future be the foundation of other nanotechnologies.

TRAMP is therefore a "projet de recherche collaborative" that deals with issues in the TRL1 to TRL4 range covered in the "défi 3" of the 2017 ANR action plan. In 'axe 4' these include "capteurs innovants à l'échelle nanométrique", "instrumentation, caractérisation, caractérisation in situ, operando", and "gestion des interfaces à l'échelle nano, fonctionnalisation, interaction entre interfaces". Since (at least) the initial tasks in the project are dedicated to experimental studies of the fundamental physical phenomenon underlying the anomalous PZR, the **TRAMP** partners also envisage the publication of results is highly visible scientific journals, and will continue to present their work at international conferences to potential academic and industrial partners as well as exploring patent opportunities for silicon based sensors.

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[10] Min-Hang Bao, Micro mechanical transducers: pressure sensors, accelerometers and gyroscopes **8** Elsevier (2000)
[11] see http://www.tronicsgroup.com/Tronics-manufactures-the-first
[12] Gartner Webinar *2Q15 Semiconductor Forecast Update*
[13] For a definition of the 'Internet of Things' see the ITU Recommendation ITU-T Y.2060
[14] Y. Choi, T. Nishida and S. Thompson, Appl. Phys. Lett. **92**, 173507 (2008)
[15] See the executive summary of the 2013 ITRS Report
[16] R. He, X. Feng, M. Roukes, and P. Yang, Nano Lett. **8**, 1756 (2008)