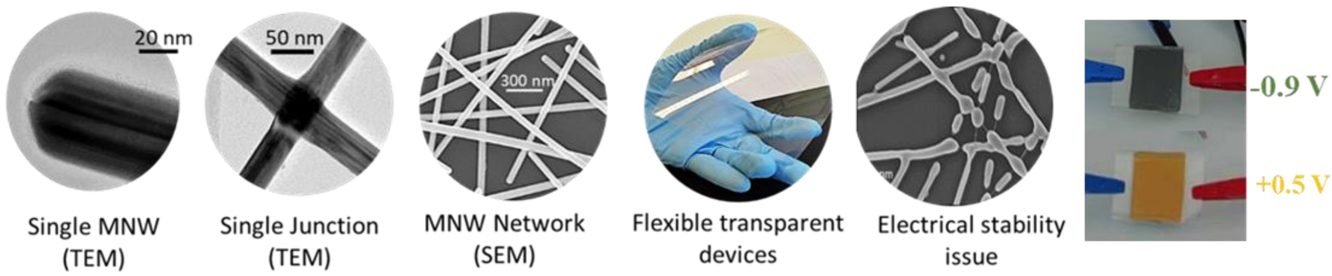
2023-2024

Internship proposal (Master or final project engineering school) at LMGP and LTM

Silver Nanowire Networks:

Effects of thin coating on their properties, stability and integration into efficient energy applications (low-emissivity, electrochromic and solar cells)

Transparent electrodes attract intense attention in many technological fields, including solar cells, OLEDs, touch screens, transparent film heaters or smart windows. New generation transparent electrodes are expected to have three main physical properties: high electrical conductivity and optical transparency and mechanical flexibility. The most efficient and widely used transparent conducting material is currently indium tin oxide (ITO). However, the scarcity of indium, associated with ITO's lack of flexibility and the relatively high manufacturing costs have prompted a search into alternative materials. With their outstanding electrical and optical properties, silver nanowire (AgNW)-based percolating networks appear to be one of the most promising alternatives to ITO for many applications[1,2]. Although the properties of these transparent electrodes are already remarkable, many problems remain to be understood, such as the network defects, the electrical homogeneity and their stability[3–6].



Electronic or optical pictures of AgNW, AgNW networks showing the different length scales that play a role, up to the electrochromic device (on the extreme right)

The goal of this internship is to better understand and optimize both properties and stability of AgNW networks, aiming for integration of these electrodes in low-emissivity coating, electrochromic or photovoltaic devices. The focus will be on the effects of metal oxide or nitride coating silver nanowires on their properties and stability. The metal oxide or nitride based coating will be deposited by Atomic Layer Deposition (ALD) and/or Spatial ALD.

The approach could be, depending on the skills/wishes of the trainee, based on:

(i) **Experimental approach**

→ Deposition of AgNWs by spray-coating technique on glass and flexible/bendable polymeric substrates

→ Optimization of coated AgNW networks through their optical, electrical and structural properties. The coating of AgNWs will be thoroughly investigated (in collaboration between LMGP, LTM and SIMAP) since it drastically enhances the stability of AgNW networks[7,8].

→ Comparison of the studied coating on the energy efficiency of the device will be assessed.

(ii) **Fundamental aspects**

→ Better understanding of the physical properties thanks to **physical modelling** and also multiscale **characterizations**

(iii) **Integration into devices** (specifically promising since this is compatible with roll-to-roll technology)

→ Integration as low-emissivity coating (for energy saving and/or thermal management)

→ Integration into electrochromic devices (searching for a performant proof of concept), in collaboration with the ICMCB laboratory in Bordeaux

→ Integration as transparent electrodes in solar cells

This internship offers a good trade-off between fundamental and experimental aspects. The candidate will get precious knowledge and skills in physics and nanomaterial sciences. The Laboratoire des Matériaux et du Génie Physique (LMGP) and Laboratoire des Technologies de la Microélectronique (LTM) house state of the art experimental equipment to fabricate Ag nanowire networks with in-situ electrical resistance measurement set-up[9]. A special attention will also be devoted to the optimization and stability enhancement of the obtained transparent electrodes and the integration of these transparent electrodes into devices will be performed[10]. For instance we have shown at LMGP that the conformal coating of AgNW by thin oxide layers leads to a much enhanced stability[7]. Simple models as well as numerical simulations will be developed to better understand the physical properties and stability enhancement[11].

Related references from the LMGP laboratory:

[1] T. Sannicolo, M. Lagrange, A. Cabos, C. Celle, J.-P. Simonato, D. Bellet, *Small* **2016**, *12*, 6052.

[2] D. T. Papanastasiou, A. Schultheiss, D. Muñoz-Rojas, C. Celle, A. Carella, J. Simonato, D. Bellet, *Adv. Funct. Mater.* **2020**, *30*, 1910225.

[3] D. P. Langley, M. Lagrange, G. Giusti, C. Jiménez, Y. Bréchet, N. D. Nguyen, D. Bellet, *Nanoscale* **2014**, *6*, 13535.

[4] M. Lagrange, D. P. Langley, G. Giusti, C. Jiménez, Y. Bréchet, D. Bellet, *Nanoscale* **2015**, *7*, 17410.

[5] S. Aghazadehchors, V. H. Nguyen, D. Muñoz-Rojas, C. Jiménez, L. Rapenne, N. D. Nguyen, D. Bellet, *Nanoscale* **2019**, *11*, 19969.

[6] V. H. Nguyen, J. Resende, D. T. Papanastasiou, N. Fontanals, C. Jiménez, D. Muñoz-Rojas, D. Bellet, *Nanoscale* **2019**, *11*, 12097.

[7] A. Khan, V. H. Nguyen, D. Muñoz-Rojas, S. Aghazadehchors, C. Jiménez, N. D. Nguyen, D. Bellet, *ACS Applied Materials & Interfaces* **2018**, *10*, 19208.

[8] L. Bardet, D. T. Papanastasiou, C. Crivello, M. Akbari, J. Resende, A. Sekkat, C. Sanchez-Velasquez, L. Rapenne, C. Jiménez, D. Muñoz-Rojas, A. Denneulin, D. Bellet, *Nanomaterials* **2021**, *11*, 2785.

[9] D. T. Papanastasiou, N. Charvin, J. Resende, V. H. Nguyen, A. Sekkat, D. Muñoz-Rojas, C. Jiménez, L. Flandin, D. Bellet, *Nanotechnology* **2021**, *32*, 445702.

[10] V. H. Nguyen, D. T. Papanastasiou, J. Resende, L. Bardet, T. Sannicolo, C. Jiménez, D. Muñoz-Rojas, N. D. Nguyen, D. Bellet, *Small* **2022**, 2106006.

[11] L. Bardet, M. Akbari, C. Crivello, L. Rapenne, M. Weber, V. H. Nguyen, C. Jiménez, D. Muñoz-Rojas, A. Denneulin, D. Bellet, *ACS Appl. Nano Mater.* **2023**, *6*, 15234.

Scientific environment: Located in the heart of an exceptional scientific environment, LMGP/LTM offer the applicant a rewarding place to work. The applicant will be integrated within a close collaboration between several scientists of LMGP and other labs (LTM, SIMAP). The LMGP works in close collaboration with LTM and SIMAP in Grenoble, and ICMCB in Bordeaux.

Laboratory website: http://www.lmgp.grenoble-inp.fr/ and https://ltmlab.fr/

Profile: We are looking for a highly motivated student who is interested to work in an inter-disciplinary project. Interpersonal skills, dynamism, rigor and teamwork abilities will be appreciated. Candidates can be fluent either in English and/or in French.
Subject could be continued with a **PhD thesis** : Yes/~~No~~.

Stipend: an internship stipend will be provided (≈600€/month for a training longer than 10 weeks)

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