Superconductor-semiconductor hybrids for quantum technologies: looking for alternatives to Al

Ayisha Ferhana[1], An-Hsi Chen[2], Amritesh Sharma[1], Amrita Purkayastha[1], Teun van Schijndel[3], Edith-Bellet-Amalric[4], Susheng Tan[5], Sergey Frolov[1], Christopher Palmstrøm[3,6,7], Moïra Hocevar[2,*]

[1]*Department of Physics and Astronomy, Univ. of Pittsburgh, Pittsburgh, USA*

[2]*Univ. Grenoble-Alpes, CNRS, Inst. NEEL, 38042 Grenoble, France.*

[3]*Electrical and Computer Engineering, University of California, Santa Barbara, Santa Barbara, CA 93106, USA*

[4]*Univ. Grenoble-Alpes, CEA, Grenoble-INP, IRIG, PHELIQS, 38000 Grenoble, France.*

[5]*Department of Electrical and Computer Engineering, Univ. of Pittsburgh, Pittsburgh, USA*

[6]*California NanoSystems Institute, University of California Santa Barbara,Santa Barbara, Santa Barbara, CA 93106, USA*

[7]*Materials Department, University of California Santa Barbara, Santa Barbara, Santa Barbara, CA 93106, USA*

*moira.hocevar@neel.cnrs.fr

The epitaxy community is making significant efforts to develop high-quality superconductor-semiconductor hybrids. These heterostructures hold promise for enabling error-limited quantum computation through qubits with longer coherence times, as well as topologically protected qubits. This effort began with the quest for improved material interfaces for gate tunable Josephson junctions using nanowires, and in particular with the development of in-situ epitaxial aluminum (Al) interfaces. However, Al is limited in terms of critical current, and many other superconductors remain underexplored. Here, we present our efforts to develop expertise in alternative superconductors such as tin (Sn) and tantalum (Ta). Both materials are known for having higher critical temperatures and higher superconducting gap than Al. However, both are allotropes, meaning they can exist in multiple crystalline phases, with only one phase being suitable for quantum bit technologies. Therefore, significant work is needed to control the crystalline phase of Sn and Ta during epitaxy or deposition to favor the desired phase. Additionally, it is critical to ensure that interfaces remain undamaged during the growth process.

Sn, for instance, has a superconducting β-phase, which is tetragonal, while its α-phase is cubic and behaves as a semimetal. Using X-ray diffraction (XRD) and transmission electron microscopy (TEM), we demonstrated that forming the β-phase of Sn on III-V semiconductors is non-trivial, particularly when depositing thin films at cryogenic temperatures. We have shown that β-phase formation depends on surface morphology (planar or nanowire) [1] and on strategies to prevent film dewetting during the return to room temperature [2]. Devices fabricated from Sn/III-V nanowires exhibit high critical currents and strong resilience to magnetic fields [1,3], which are essential properties for quantum devices such as Josephson parametric amplifiers, gatemons, and Majorana-based systems. Yet, one drawback of Sn is that the oxide on its surface causes losses in microwave resonators made from this superconductor. An alternative material could be Ta, as resonators built with tantalum have demonstrated performance comparable to those made with aluminum. The α-phase of Ta is the "holy grail," as it exhibits a higher critical temperature. Achieving control over the growth of this phase requires either cryogenic temperatures and the use of titanium sticking layers or very high temperatures incompatible with III-V materials. Preliminary data on the former approach will be presented.

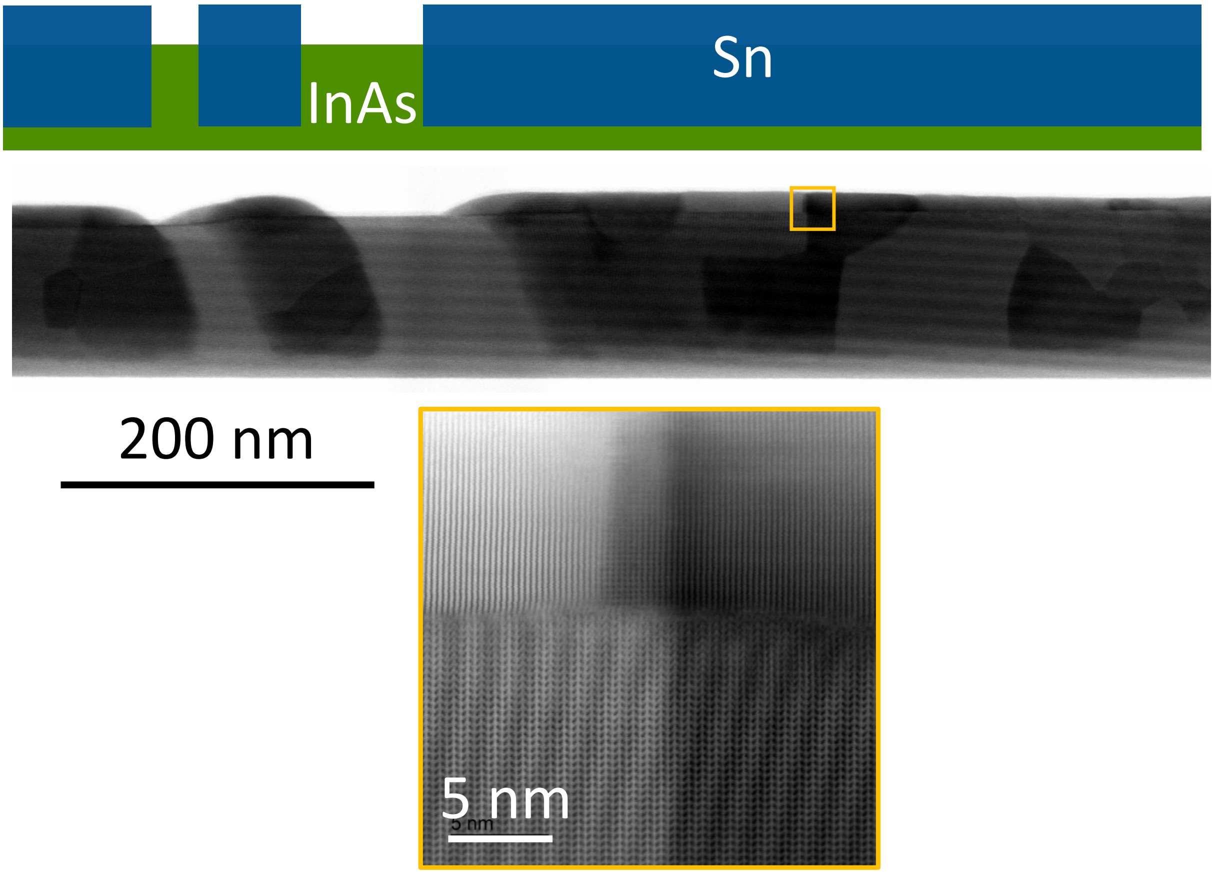

Figure 1: High-resolution bright field transmission electron micrograph of a partial shell of Sn grown on an InAs nanowire. The structural analysis of the shell shows that the grains have the β-phase and are in grain by grain epitaxial relation. Moiré patterns appear by superposition of the InAs and Sn lattices.

References:

[1] M. Pendharkar et al, Science (2021)

[2] A. H. Chen et al, Nanotechnology (2023)

[3] A. Sharma et al, in preparation (2024)

Acknowledgments: This work was supported by ANR HYBRID (ANR-17-PIRE-0001), IRP HYNATOQ and the Transatlantic Research Partnership.