Pushing group IV epitaxy by means of UHV-CVD: high-quality Ge/SiGe heterostructures for integrated photonic devices

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The Ge and Ge-rich multilayers are attracting a growing interest due to their CMOS compatibility and the wide range of possible applications, spanning from far- and mid-infrared integrated photonics to quantum computing. Their widespread adoption is however hindered by the difficulties arising from the large lattice mismatch between Si and Ge, and the need to manage the strain by introducing strain-compensation in the superlattice. Moreover, controlling the heteroepitaxial growth at the sub-nm scale is mandatory to enable a material platform for the development of novel complex heterostructures and low dimensional systems.

Here we present how the growth of high-quality strain balanced, multi-μm-thick stack of Ge/SiGe heterostructures on Si(001) and on Silicon on Insulator (SOI) substrates can be achieved by using ultra-high-vacuum chemical vapour deposition (UHV-CVD). First, we focus on Ge/SiGe multilayers designed as an active material for a quantum cascade laser operating in the THz spectral region [1] which represent the ultimate challenge for a heteroepitaxial deposition process requiring the growth of several μm thick, strain-compensated active regions, comprising hundreds of quantum wells (QWs) coupled by ultra-thin tunneling barriers (~ 1 nm). To assess the level of control reached in the deposition of such structures, we combine a thorough structural investigation by high resolution X-ray diffraction, scanning transmission electron microscopy, atom probe tomography, secondary ion mass spectroscopy, and atomic force microscopy, with THz spectroscopy absorption measurements and simulations. We achieved a state-of-the-art threading dislocation density ~10^6cm^{-2}, ultra-sharp interfaces, a sub-nm control over the SiGe composition profile, the control of dopant atoms position at the nanoscale, and reproducibility within 1% of the layer thickness and composition within the whole multilayer stacks, thus overcoming all the critical issues arising in the heteroepitaxy process of such demanding devices [2]. Furthermore, t we demonstrate the ability to grow QWs with an arbitrary compositional profile, such as parabolic and triangular QWs, opening the route to the engineering of optimized potential profiles for carriers in quantum devices [3].

Our results suggest that UHV-CVD achieves both the sub-nm control typical of molecular beam epitaxy and the high growth rate and technological relevance of chemical vapor deposition. Thus, this technique is a key enabler for the deposition of integrated photonic devices and other complex quantum structures based on the Ge/SiGe material system.

References (if needed)

[1] T. Grange, et al., "Room temperature operation of n-type Ge/SiGe terahertz quantum cascade lasers predicted by non-equilibrium Green's functions, Applied Physics Letters 114, 111102 (2019).
[2] E. Talamas Simola et al.," Subnanometer Control of the Heteroepitaxial Growth of Multimicrometer-Thick Ge/SiGe Quantum Cascade Structures" Phys. Rev. Applied 19, 014011 (2023)
[3] M. Montanari et al. "THz intersubband absorption in n-type Si_{1-x} Ge_x parabolic quantum wells", Applied Physics Letters 118, 163106 (2021).