Strain control, imaging and tuning developed for SiGe qubit devices

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Quantum hardware based on Si and Ge present the advantage of integration and scalability due to compatibility with the mainstream C-MOS semiconductor industrial technology. In addition to the unique crystalline perfection, these materials can be isotopically purified further improving their spin coherence time. The challenge in the indirect semiconductors Si and Ge is to lift the six-fold valley degeneracy in order to isolate proper qubits. This requires quantum well heterostructures with well-defined interface sharpness and most importantly a well-controlled level of homogeneous strain [1].

Biaxial strain of the order of 1 % in 10 nm quantum wells is achieved on mismatch-tuned substrates based on strain-relaxed buffers (SRBs) of $Si_{1-x}Ge_x$ alloys with Ge-content x graded up to the required relaxed lattice of the mismatched seed. However, the intrinsic defect structure of such SRBs leads at their surface to lattice parameter variations reproduced in the overgrown epitaxial layers. The ID01 beamline located at the European Synchrotron offers X-ray nanobeam diffraction imaging, a tool essential to image and study strain in such quantum wells with high spatial and strain resolution [2-4]. Typical images of an SRB and an overgrown qubit device are shown in Fig. 1(a) and (b). As strain directly affects band structure, these lattice parameter variations trigger spatial fluctuations of the conduction band minima and the expected band degeneracy lifting. These defects in the end jeopardize the functionality of the qubit devices.

To avoid such strain fluctuations, we developed a technique to strain a semiconductor membrane by external mechanical means, yielding a spatially homogeneous and controlled deformation. Using an elastomer- semiconductor hybrid structure, we demonstrate straining membranes far beyond the traditional straining by epitaxial methods, in terms of strain amplitude (up to 2 % biaxial in a Si 200 nm membrane), strain homogeneity, and strained film thickness. We estimate this technique to open up a road towards the fabrication of high quality strained structures for Si and Ge based quantum computing.

References

[1] F. A. Zwanenburg *et al.*, Reviews of modern physics, 85 (2013) 961
[2] P. Evans *et al.*, Adv. Mater. 24 (2012) 5217
[3] M.-I. Richard *et al.*, ACS Applied Mater. Interfaces, 7 (2015) 26696
[4] C. Wiciak *et al.*, ACS Appl. Mater. Interfaces, 15 (2023) 3119
[5] T. U. Schulli *et al.*, submitted Materials Today advances 2024,

Figures

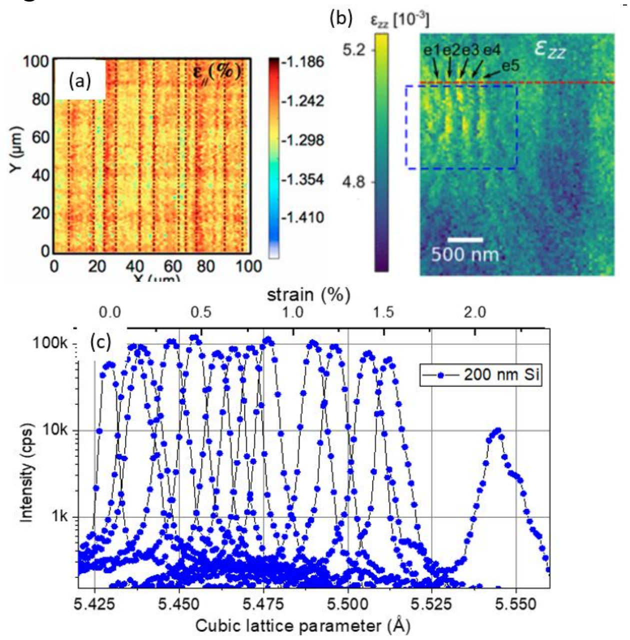

Figure 1: (a) X-ray nano-beam imaged biaxial strain in a SRB based surface (from [3]). **(b)** similar image of strain in and around a qubit device (from [4]). **(c)** biaxial strain tuning in a polymer-Si compound based process (from [5])