EUROPEAN SYNCHROTRON RADIATION FACILITY

INSTALLATION EUROPEENNE DE RAYONNEMENT SYNCHROTRON

ESRF	**Experiment title:** Towards improved spin qubit quality: Low temperature determination of strain fluctuations in Si/SiGe induced by TiN surface electrodes	**Experiment number:** MA-5128
Beamline: ID01	**Date of experiment:** from: 01-06-23 to: 06-06-23	**Date of report:**
Shifts: 15	**Local contact(s):** Edoardo Zatterin	*Received at ESRF:*

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Report:

The aim of this proposal was to characterize the local strain fluctuations underneath devices for coherent shuttling of electrons ("QuBus", **Fig. 1**) in epitaxial Si$_{0.7}$Ge$_{0.3}$ / 10 nm Si / Si$_{0.7}$Ge$_{0.3}$ heterostructures, [1] similar to a study we published on functional qubits housed in a Ge/ Si$_{0.2}$Ge$_{0.8}$ layer. [2] The Si/Si$_{0.7}$Ge$_{0.3}$ layers were grown by reduced pressure chemical vapor deposition (RP-CVD), a SiO$_2$ dielectric layer was deposited by CVD, and the electrodes for the QuBus devices were fabricated by sputter deposition and lithography on the sample surface. During this beamtime, we studied two types of samples: (1) QuBus devices with a small gate pitch of ~ 140 nm fabricated with metallic Palladium (Pd) gates with e-beam lithography by an academic research group, (2) devices with a larger gate pitch of ~ 320 nm, fabricated by from Titanium Nitride (TiN) by optical lithography in an industrial cleanroom by a CMOS process.

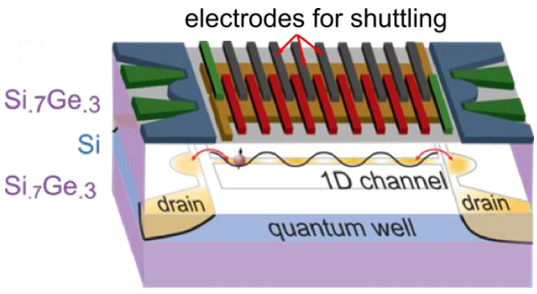

Fig. 1: Schematic of a QuBus on Si/Si$_{0.7}$Ge$_{0.3}$

To map the strain distribution around the QuBus within the 10 nm thin strained Si quantum well (QW), a spatially resolved, non-destructive technique with high lattice sensitivity is needed. Thus, in-situ nano-beam scanning X-ray diffraction microscopy (SXDM) at ID01, is the technique of choice for this research.[3] To observe the strain fluctuations relevant for real QuBus devices, measurements were planned both at room temperature (RT) and at low temperature (LT) close to the QuBus operation condition (< 2 K). Fluctuations of strain due to the electrodes are expected to strongly influence the performance of quantum devices.[2] At LT, the strain distribution will be different compared to RT because of thermal contraction.[4,5] However, due to previously observed mechanical vibrations within the cryostat, measurements of the type (1) devices at LT were not feasible. Therefore, RT measurements were performed on type (1) samples, while LT measurements were

focussed on type (2), which was characterized at RT during a previous beamtime (ma4702).
During the experiment, the X-ray energy was set to 7.79 keV and the beam focussed to ~ 50 nm spot size. The focussing optics consisted of Fresnel Zone Plate (FZP), Beam Stop (BS) and Order Sorting Aperature (OSA). The piezo scanners were placed below the OSA to scan the beam rather than the sample to perform mappings on samples in the cryostat. An energy resolved X-ray fluorescence detector was mounted to measure Pd or Ti fluorescence signals simultaneously to the diffraction. Diffraction maps were measured around the QuBus for several Bragg reflections from the {2 2 4} family of planes.

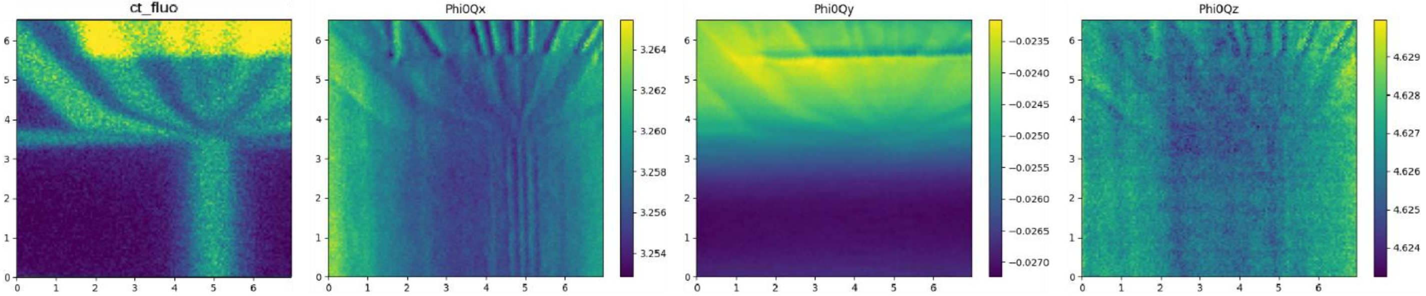

Fig. 2: Maps of the Pd X-ray fluorescence **(left)** and the three components of the scattering vector (in nm^{-1}) from the Si QW layer for a sample with small Pd electrodes fabricated by e-beam lithography.

The measurements at RT were performed without the cryostat. The larger electrodes are well resolved in the diffraction signal from the Si QW (**Fig. 2**), however the small Pd claviature electrodes are barely visible. We expect reconstruct the strain landscape with a lateral resolution of ~50 nm, but this may be insufficent to resolve the details of the strain features within the sample of type (1) with very small lithograpic structures.

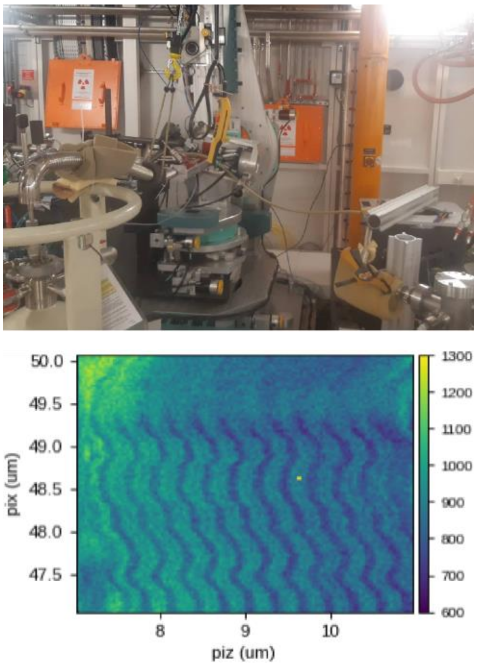

Fig. 3: (top) Setup to stabilize the cryostat and reduce mechanical vibration; (bottom) diffraction map of a TiN QuBus sample at LT, showing the undulations due to convection of liquid He in the cryostat.

For the measurements at LT, the sample was placed in a liquid He flow cryostat and the temperature was kept stable at 4 K. We attempted to minimize the mechanical vibrations by taking steps to stabilize the setup (**Fig. 3, top**), including supporting the He line with a crane, wrapping all moving parts with insulating foam and placing the He pump on a raised platform. However, the vibrations could not be entirely supressed. In all highly resolved mappings within the cryostat, irregular spatial undulations appear along the slow scan axis (**Fig. 3, bottom**). These fluctuations seemingly occur on timescale of several seconds. We were able to determine that they are caused by the convection of the He in the cryostat rather than vibrations from the pump, since they only appeared when the He valve was opened. When the He valve was closed, no undulations appeared, regardless if the pump was switched on or off.
Due to this instability, the data analysis of these maps is demanding, but we anticipate that a line-by-line correction of the “footprint” from the TiN claviature electrodes with large pitch may be possible, to reconstruct their regular and periodic shape.
In total, one sample was investigated at RT and one sample at LT during this beam time. For each sample, around a QuBus device several datasets were recorded for different asymmetric Bragg reflections from the. By overlapping the diffraction maps for the different reflections, it will be possible to determine the lattice parameters in both in the thin Si QW and the thick Si$_{0.7}$Ge$_{0.3}$ buffer. This will allow for independent, model-free calculations of the strain tensor. For the characterization of very small, functional devices we anticipate that more highly resolved methods, such as lens-less Bragg Coherent Diffraction Imaging (BCDI) may be required.[6] From the LT data we collected, we anticipate that a dedicated data analysis procedure can be developed, allowing to remove the irregular undulations from the maps based on a reference image of the larger QuBus structure. This would open a path towards the characterization of the strain landscape of cryogenic device *in-situ*, at their operation temperature.

References

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