QUANTUM DOT CSD SIMULATION AND AUTOMATED CHARGE TRANSITION DETECTION

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1. MOTIVATION

- Semiconductor quantum dot qubits are controlled via gate voltages
  - Plunger gates (P1 - P4 in Fig. 1) control the dot potentials
  - Barrier gates (B1 - B5 in Fig. 1) control the tunnel barriers
- Tuning large numbers of qubits requires automation
  - Correct number of charges must be trapped in each quantum dot
  - Number of charges is derived from charge transitions in charge stability diagrams (CSDs), in this case measured using a sensor dot

→ Automatic detection of charge transitions enables tuning automation
  → Goals: good generalization and low complexity, to enable a cryogenic hardware implementation

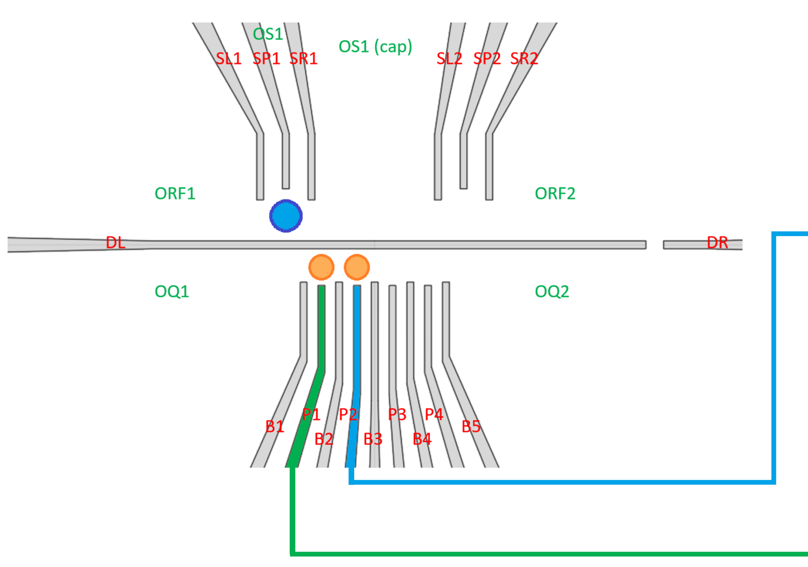


Fig. 1: Example of the gate layout of a semiconductor quantum dot sample (by T. Hangleiter, RWTH, similar to [1]). The blue/orange circles illustrate the regions in which sensor/quantum dots are formed.

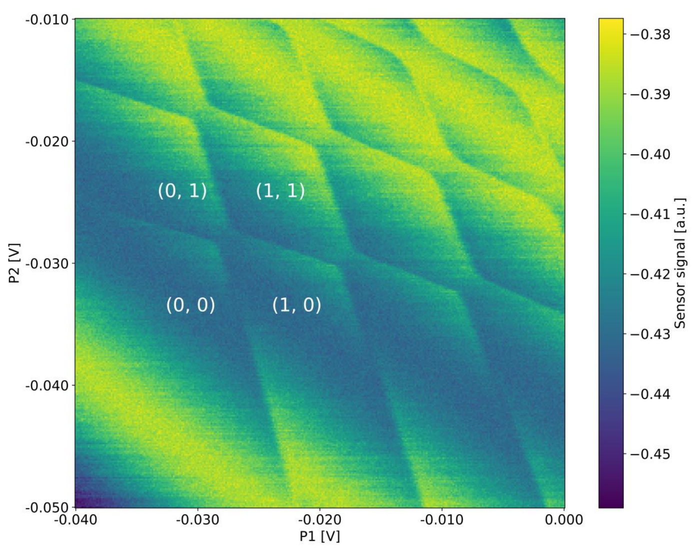


Fig. 2: Example of a CSD for a well behaving double quantum dot. The lines indicate a transition of electrons into or out of a dot. In parentheses: exemplary double quantum dot occupation numbers.

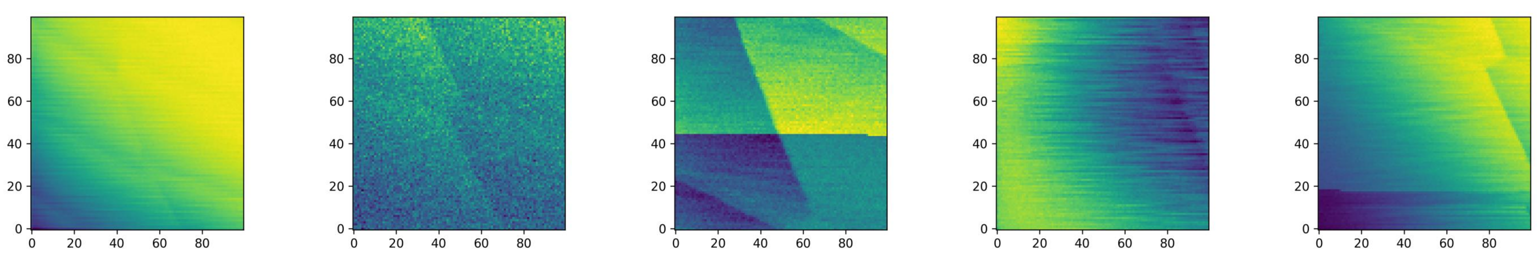


Fig. 3: Examples of measured CSDs with typical distortions. CSDs may feature only weak structures or are affected by strong white noise, random telegraph noise (RTN), and pink noise.

2. SIMULATION FRAMEWORK SIMCATS

- **Sim**ulation of **C**SDs for **A**utomated **T**uning **S**olutions [2] (Python pack. [3])
- General, flexible simulation framework with interfaces for
  - idealistic CSD simulation
  - sensor reaction simulation
  - simulation of distortions affecting idealistic CSD data, corresponding sensor potential, and sensor response
- Includes standard implementations and corresponding configurations
  - Geometric CSD model, Lorentzian sensor peak, white noise, pink noise, random telegraph noise, dot jumps, transition broadening

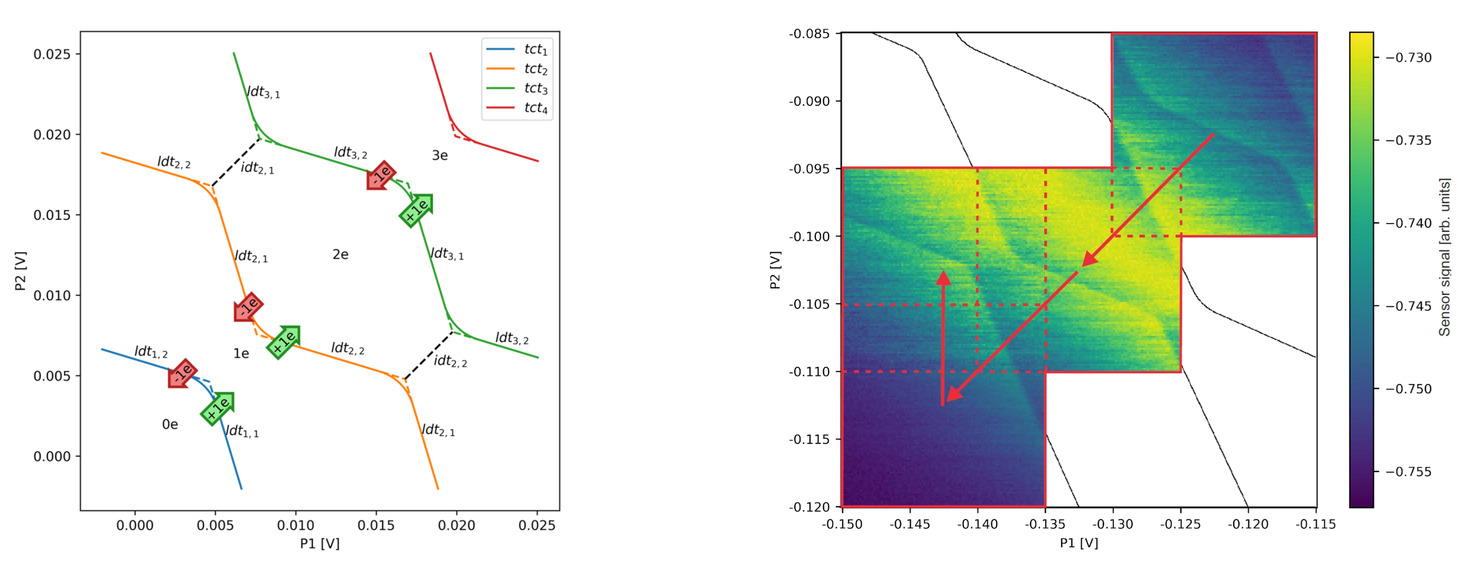


Fig. 4: Left figure: Structural representation of CSDs used for the geometrical simulation, based on total charge transitions (TCTs). Right figure: Sequential data simulation in the voltage space. Figures taken from [2].

3. CHARGE TRANSITION DETECTION

Investigated Approaches

- Classical (gradient-based, phase-congruency-based, and mixed)
- Machine learning (convolution-, transformer-, state-space-model-, and diffusion-based)

CSD Data

- Training: 1,000,000 simulated CSDs (geometrical SimCATS model [2])
- Validation: simulated + experimental CSDs [4]

Key Observations

- Algorithms trained on simulated data can generalize to experimental data
- U-Net like architectures performed best
- Diffusion-based approaches too complex for hardware implementation
- Convolution based architectures are sufficient
- Tiny versions (e.g. UNet-38k) show competitive results

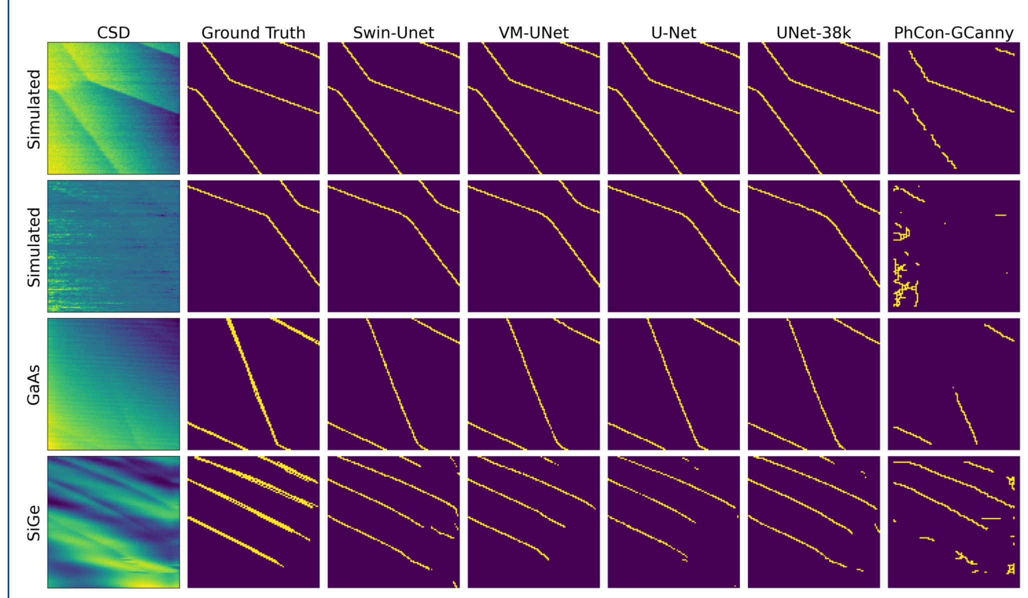
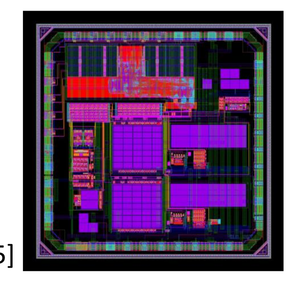


Fig. 5: Charge transition detection on simulated and experimental (GaAs & SiGe) evaluation datasets.

Detector	Category	SDICE
Swin-Unet	Transformer	0.935
VM-Unet	State-space	0.935
U-Net	Convolution	0.931
UNet-38k	Convolution	0.890
MedSegDiff-V2	Diffusion	0.855
PhCon-GCanny	Classical	0.678

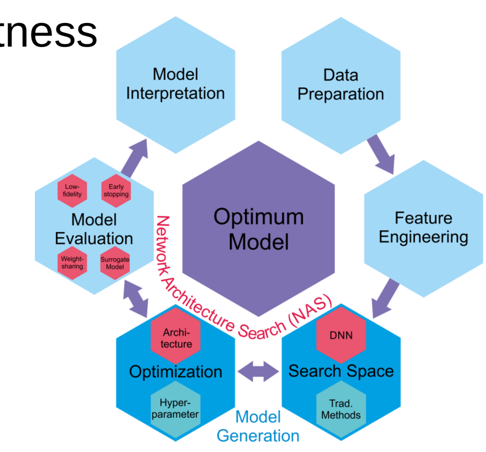
Tab. 1: Surface-DICE (SDICE) of categories' best approach (experimental GaAs dataset).

4. OUTLOOK

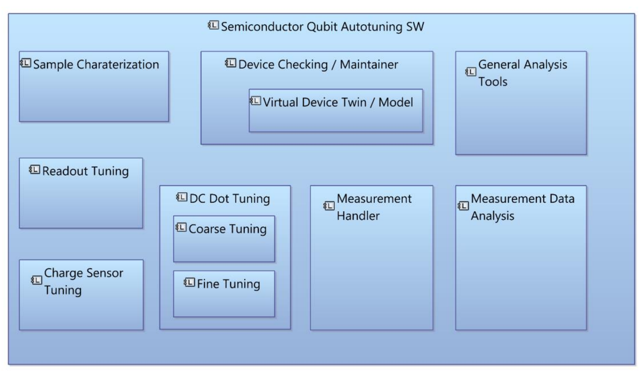


[5]

- Tiny convolution-based approaches are exciting candidates for cryogenic hardware implementation
- Further complexity reduction & improvement of robustness
  - Reduced data representation (quantization)
  - Automated Machine Learning (AutoML)
    - Hyperparameter Optimization (HPO)
    - Neural Architecture Search (NAS)
  - Introduction of verification strategies & explainable AI (XAI)



- Extendable automatization framework
  - Sensor tuning
    → Simulation of sensor tuning data
  - Quantum dot coarse & fine tuning
  - Readout



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[1] C. Volk et al. - Loading a quantum-dot based Qubyte register; DOI: 10.1038/s41534-019-0146-y
[2] F. Hader et al. - Simulation of Charge Stability Diagrams for Automated Tuning Solutions (SimCATS); DOI: 10.1109/TQE.2024.3445967
[3] F. Hader et al. - Simulation of Charge Stability Diagrams for Automated Tuning Solutions (SimCATS); www.github.com/f-hader/SimCATS
[4] Provided by the Quantum Technology Group of RWTH Aachen (www.quantuminfo.physik.rwth-aachen.de/cms/quantuminfo/forschung/~xwpl/quantum-technology-group/)
[5] Mair et al. - Rapid Prototyping Platform for Integrated Circuits for Quantum Computing; SMACD Conference 2024 Greece