AUTOMATIC DETECTION OF CHARGE TRANSITIONS IN CHARGE STABILITY DIAGRAMS

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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 for scalability

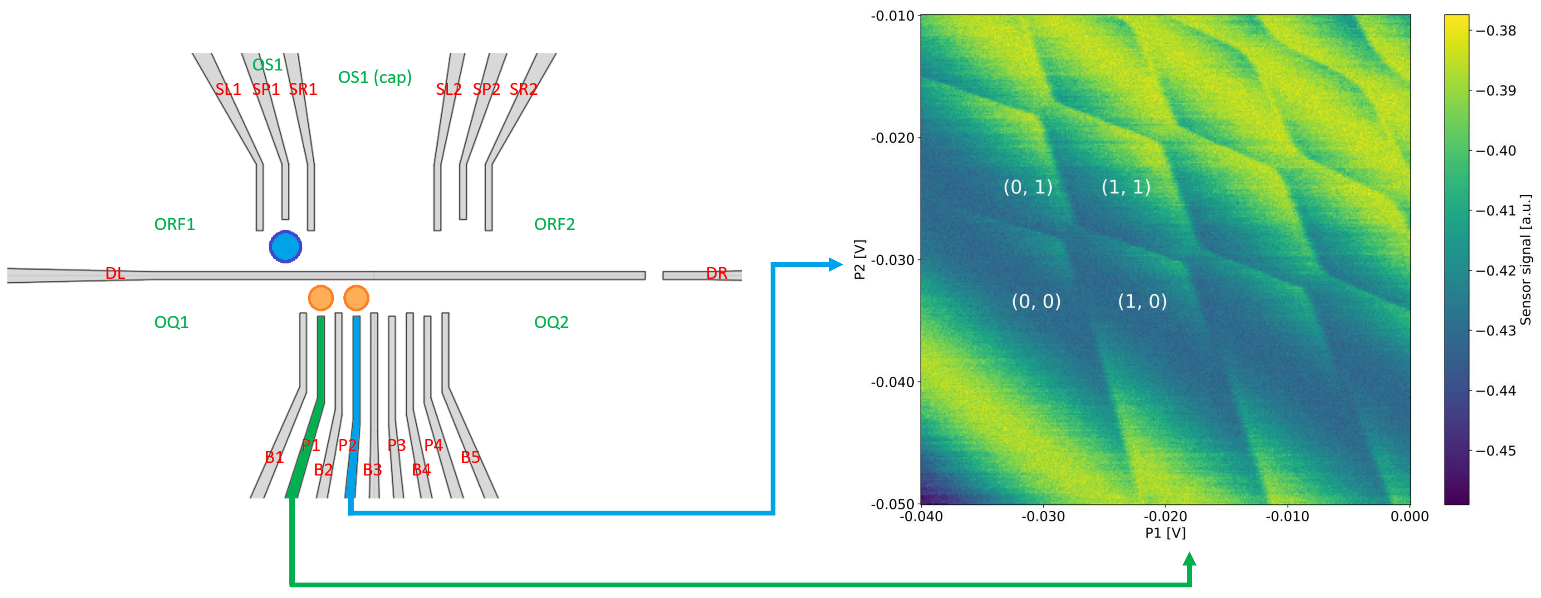

Fig. 1: Example of the gate layout of a semiconductor quantum dot sample (by T. Hangleiter, RWTH, similar to [1]). The blue/orange circles illustrate the regions in which sensor/quantum dots are formed.

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.

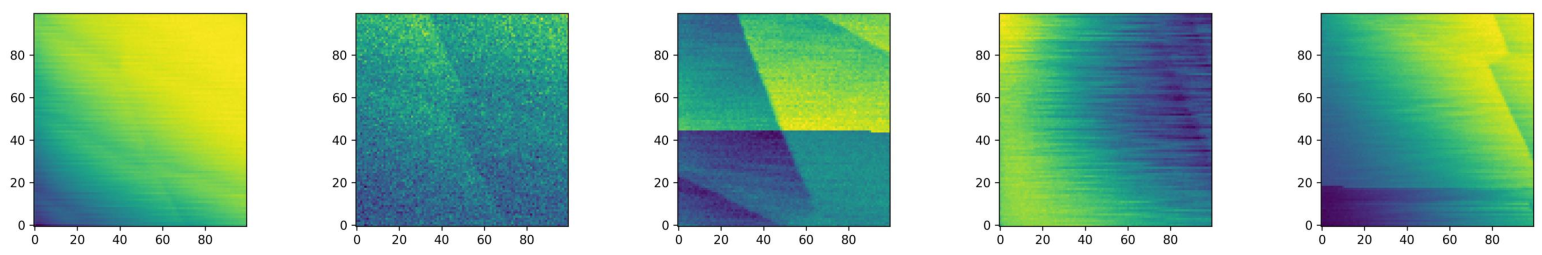

Fig. 3: Examples of measured CSDs with typical distortions. CSDs may feature only weak structures or are affected by strong white noise, random telegraph noise (RTN), and pink noise.

2. METHODS / ALGORITHM DEVELOPMENT

Traditional approaches

- Gradient based
- Phase congruency based (novel approach)
- Mixed approaches

Machine learning

- Convolution based
- Transformer based
- State space model based
- Diffusion based

CSD Data

- Simulated data from the geometric SimCATS model [2] for parameter optimization and training
  - Pink, white & random telegraph noise, transition blurring, and dot jumps
  - Random variations of charge transitions, sensor, and distortions
  - 10.000 randomly sampled configurations with 100 CSDs each
- Simulated data + experimental data for validation

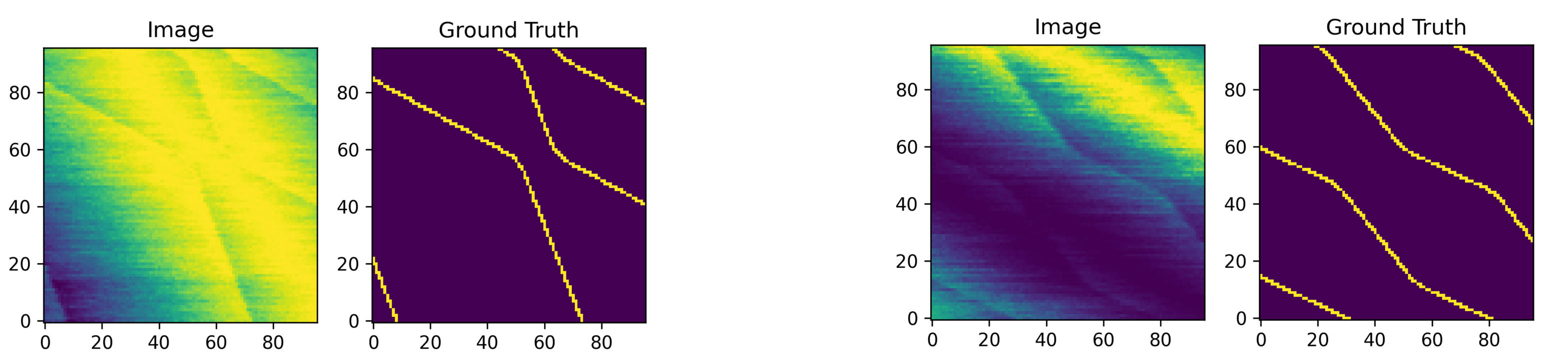

Fig. 4: Examples of simulated CSDs with corresponding ground truth.

3. EXEMPLARY RESULTS

Canny Approach (Traditional, Gradient Based)

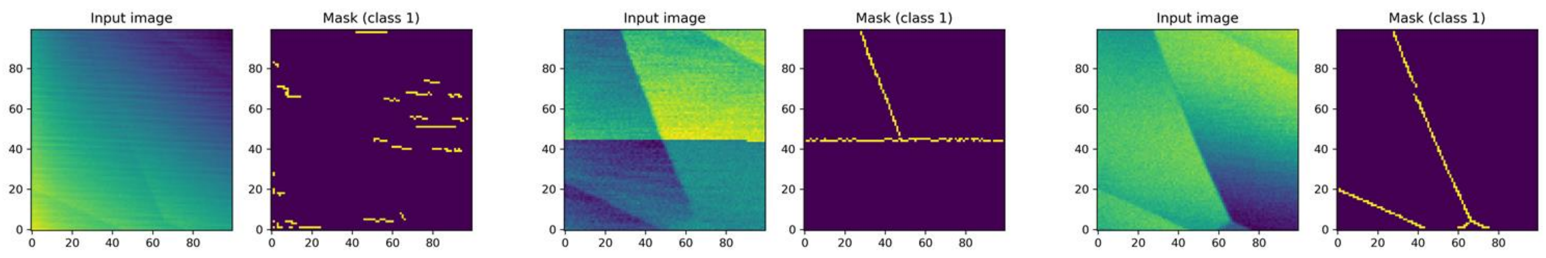

Fig. 5: Charge transition detection on experimental data from the GaAs qubit sample shown in Fig. 1. *Left CSD*: no valuable information is extracted; *center CSD*: RTN is detected as charge transition and multiple transitions are missing; *right CSD*: the majority of charge transitions is detected.

Tiny UNet (Machine Learning, Convolution Based)

- Model size reduced by more than 99% (compared to classical UNet)

Tab. 1: Statistics for a tiny version of a UNet model developed at ZEA-2. Metrics have been calculated on a simulated validation set.

Model Type	Model Size	Jaccard Similarity	Dice Score	Inference Time (Nvidia L4)
U-Net (Bilinear Upsampling)	67,425 params	0.872	0.915	1.15 ms

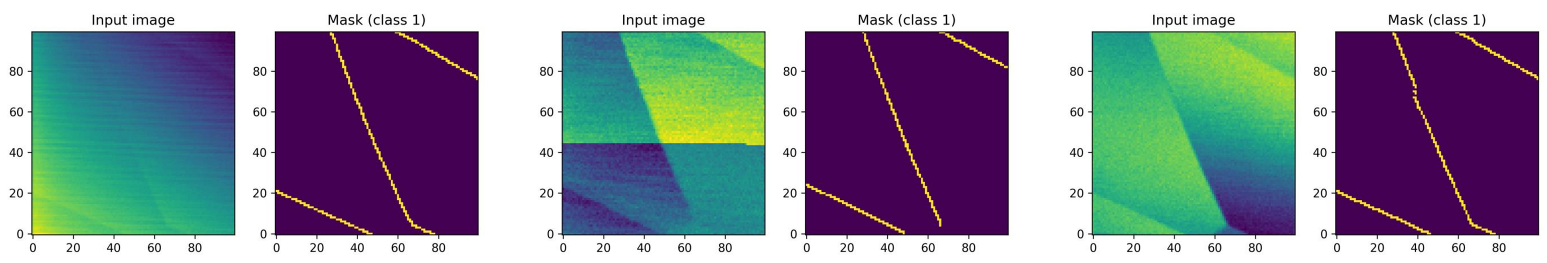

Fig. 6: Charge transition detection on the same experimental data as shown in Fig. 5. All charge transitions are detected. The network ignores the RTN in the center CSD without leading to a wrong detection.

4. OUTLOOK

- Final evaluation & selection of machine learning and traditional approaches
- Testing with further experimental data
  - SiGe sample
  - Live in the experiment

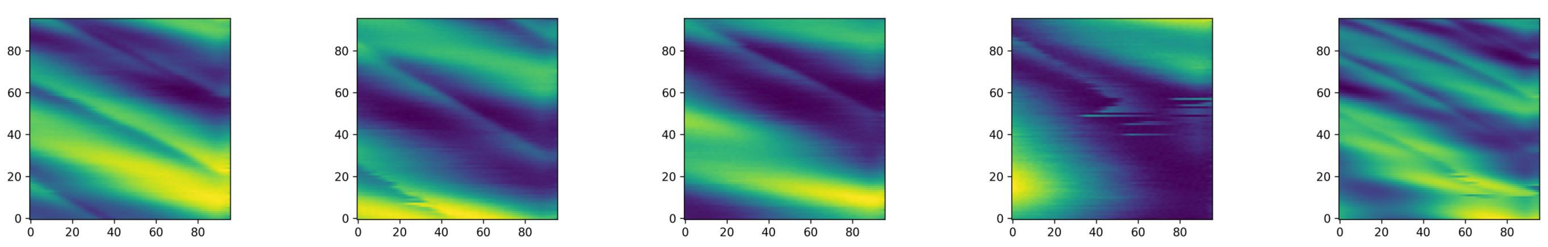

Fig. 7: Examples of single dot plunger vs. barrier CSDs from a SiGe sample.

- Further complexity reduction & improvement of robustness
  - Automated machine learning (AutoML)
  - Hyperparameter optimization (HPO)
  - Neural Architecture Search (NAS)
  - Introduction of verification strategies & explainable AI (XAI)

→ Long term goal: hardware implementation

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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: 10.36227/techrxiv.171173496.61131656/v1