

# SENSOR SCAN SIMULATION FOR AUTOMATED TUNING OF GATE-DEFINED SEMICONDUCTOR QUANTUM DOTS

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## 1. MOTIVATION

- Sensor dots (SD) in double quantum dot (DQD) spin-qubits:
  - Resolve DQD charge changes for qubit tuning and readout via the SD
  - Requires a stable and sensitive sensor, achieved through sensor scans
- Tuning a substantial quantity of qubits necessitates automation
- Algorithm development requires substantial amounts of labeled data
  - Especially for testing and comparison of algorithms
- Manually measuring and labeling is inherently time-consuming
  - Solution: Simulation of sensor scans for sensor tuning and charge stability diagrams (CSD) for charge state tuning

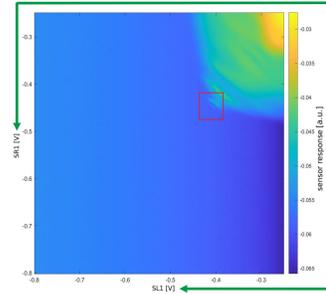


Fig. 1: Example of a sensor scan. The green arrows illustrate the two gates that are swept over a specific voltage range, during the measurement of the sensor response. Figure taken from [1].

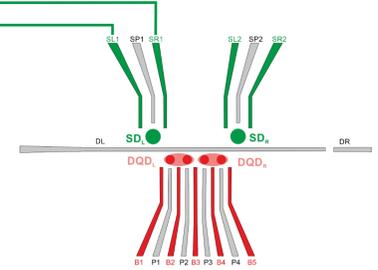


Fig. 2: Example of the gate layout of a semiconductor double quantum dot (RWTH Aachen Univ., similar to [2]). The green/red circles illustrate the regions in which sensor/quantum dots are formed. Figure taken from [3].

## 2. SIMCATS



- Simulation of CSDs for Automated Tuning Solutions [4]
- A general, flexible simulation framework with interfaces for:
  - Idealistic CSD simulation
  - Sensor signal simulation
    - Lorentzian sensor peak
  - Simulation of distortions
- Includes standard implementations, corresponding configurations and samplers for configurations

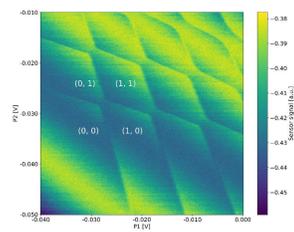


Fig. 3: Example of a charge stability diagram for a well behaving double dot simulated using SimCATS.

## 4. MODEL FOR SENSOR SCANS

- Physical models for single electron transistors used as sensor dot
  - Physical properties of the sample must be ascertained
  - Labels are not directly included
  - Do not feature all relevant effects or are too computationally complex
- Empirical modeling approach
  - Flexible way to picture various structures
  - No physical parameters required
  - Easy to simulate measurements
  - Fast calculation & already labeled data
  - Sensor simulation fully integrated into the SimCATS framework

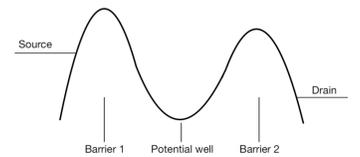


Fig. 5: Visual representation of the potential landscape of the sensor dot. The potentials are influenced by the voltages applied to the gates.

## 3. SOFTWARE DESIGN

- Implemented as an Extension of the SimCATS Framework
  - Enables combination of sensor & CSD simulation
- Extensibility and interchangeability as core design principles
- Usage of the Strategy Pattern
  - Implemented through interfaces
  - Used for the sensor class, sensor & barrier functions and distortions & deformations
- Metadata of simulations is returned in addition to the result
  - Reconstructable simulations via metadata

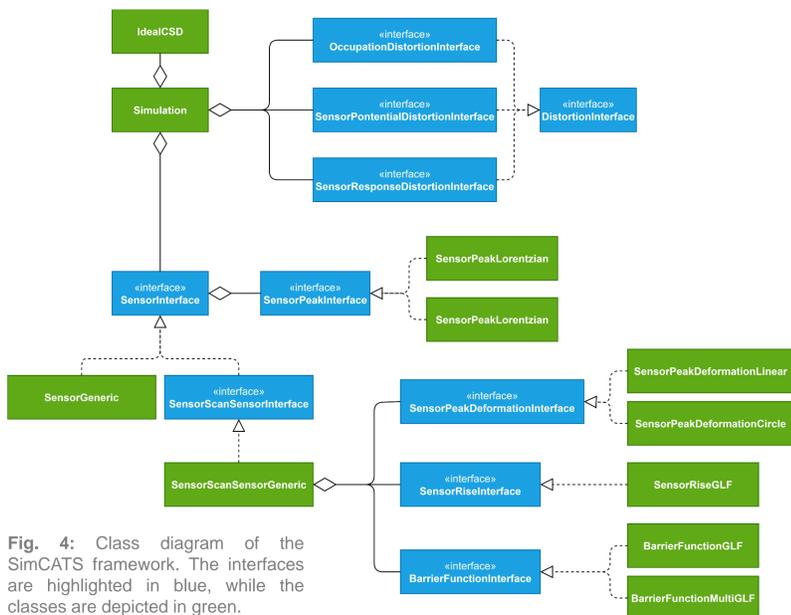


Fig. 4: Class diagram of the SimCATS framework. The interfaces are highlighted in blue, while the classes are depicted in green.

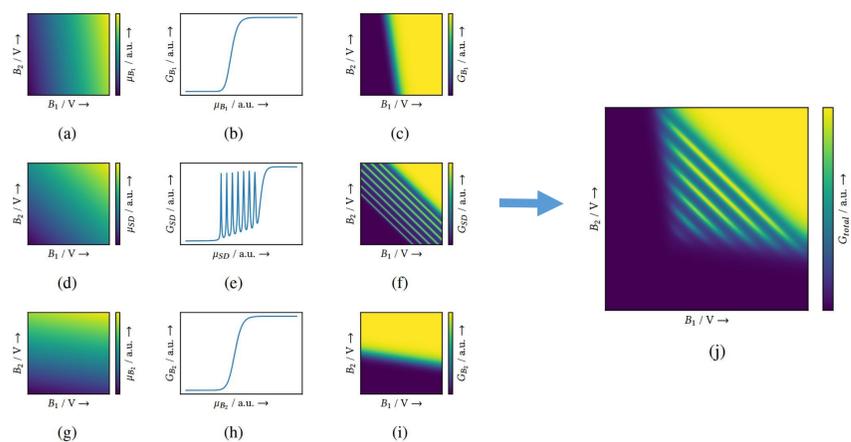


Fig. 6: Illustration of the calculation of a simulated sensor scan. For the simulation, the three potentials of barrier 1 (a), the sensor dot itself (d), and barrier 2 (g) are initially calculated. The application of barrier and sensor functions (b), (e), (h) results in the subsequent calculation of respective conductance values (c), (f), (i). These values are then combined to the simulation result (j) akin to three resistances in series.

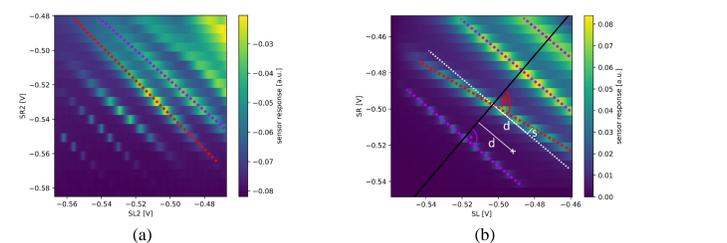


Fig. 7: Example of sensor scans with deformed peaks. (a) Displays an experimental sensor scan featuring deformed peaks. (b) Illustrates the simulation of linearly deformed sensor peaks.

## 5. OUTLOOK

- Usage for simulation-based development of tuning algorithms for the sensor dot
  - Enables fast, reproducible, controlled development and testing
  - Currently used for a ray-based algorithm for Coulomb oscillation area detection
- Sensor scan simulation will be published soon as SimCATS extension
- Usage of the simulation for further algorithm development and refinement
- Testing of sensor dot tuning in an experiment
  - Integration of the algorithms within the cryostat close to the qubit
  - Further optimization to minimize resource consumption for potential



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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. "Noise Analysis and Estimation in Sensor Dot Fine Scans for Automated Tuning of Gate Defined Quantum Dots". MA thesis. Fachhochschule Aachen, 2021.

[3] S. Fleitmann. "Characterization of Distortions in Charge Stability Diagrams and Their Simulation in Modeled Data". Master thesis. Jülich: FH Aachen, 2023, p. 84. DOI: 10.34734/FZJ-2024-00621.

[4] F. Hader, S. Fleitmann and F. Fuchs. SimCATS. URL: https://github.com/fzj-ica/SimCATS