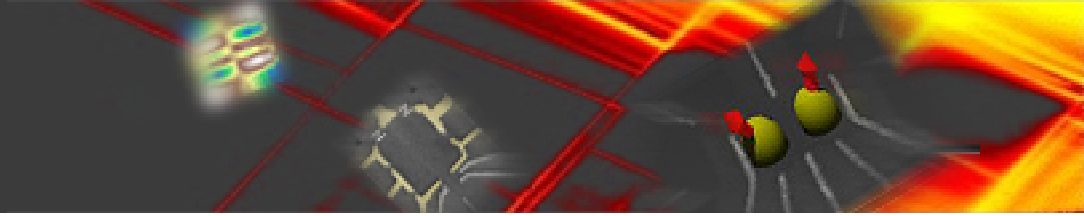

Real-Time Feedback Control of Charge Sensing for Quantum Dot Qubits

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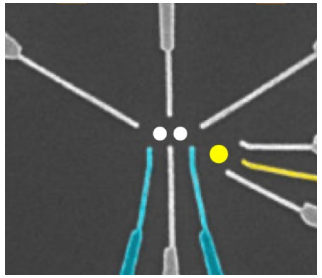
Motivation

- Operating window of charge sensor is smaller in few-electron regime where sensitivity is increased → subtle tuning of sensor required

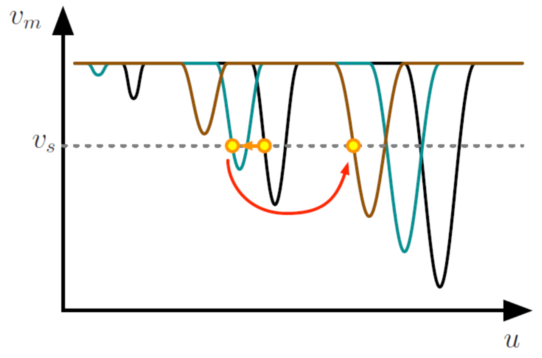
- Here: Automated real-time tuning of a charge sensor for spin qubit experiments in a $Si/Si_{0.7}Ge_{0.3}$ DQD device



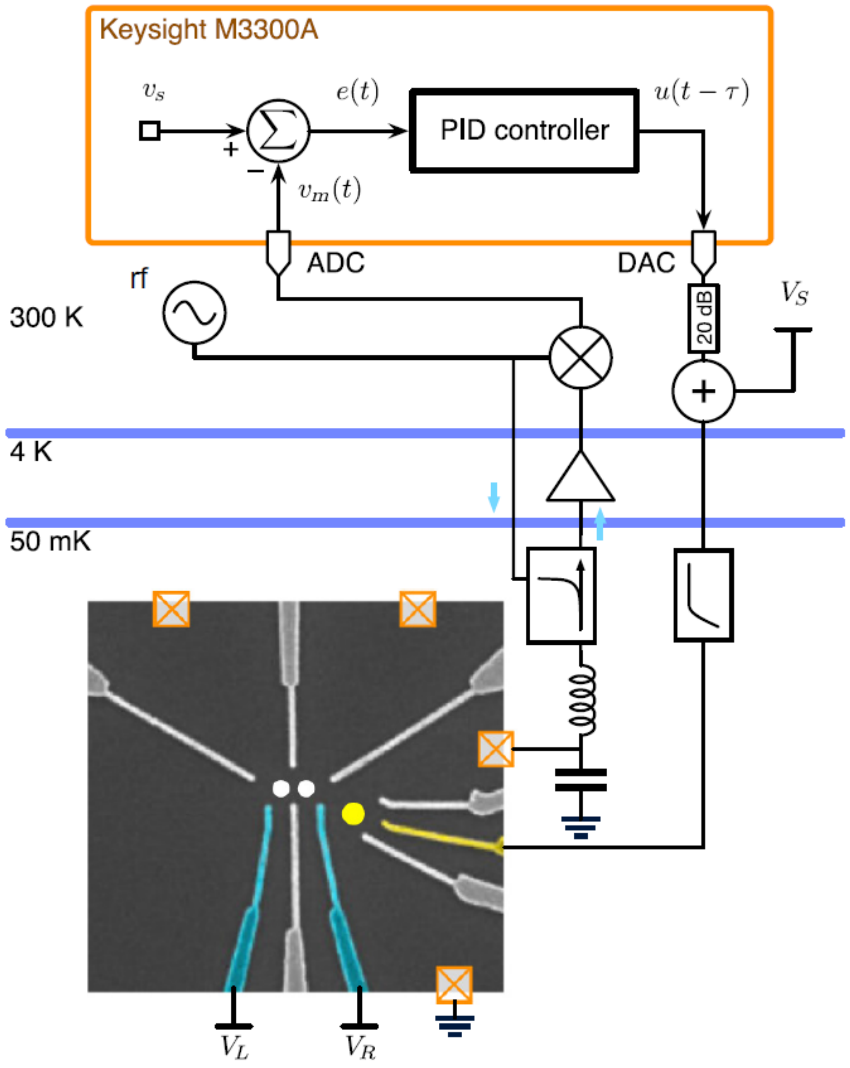
- Compensation of slow disturbances up to 100 kHz using a digital Proportional-integral-differential (PID) controller

- Demonstrations of the feedback loop:
  -> Charge stability diagrams
  -> Single-shot spin measurement

- Demodulated rf-signal v_m sampled at 100 MSa/s
- v_s: desired setpoint
- $e(t) = v_s - v_m(t)$



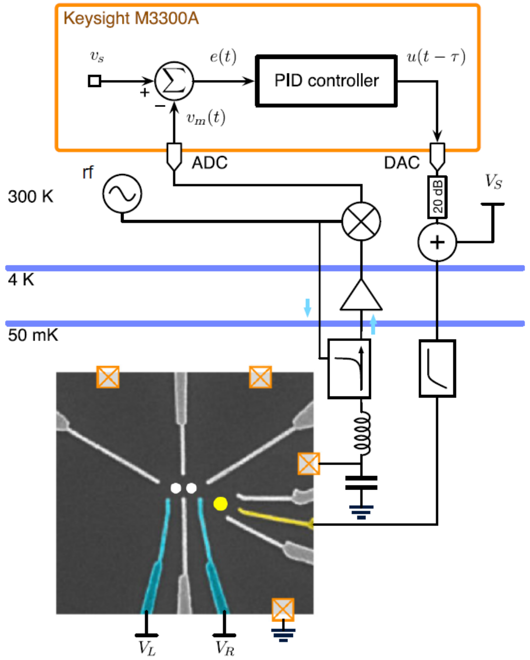
- PID controller: $u(t) = K_p e(t) + K_i \int_0^t e(s)ds + K_d \frac{de(t)}{dt}$
- Control voltage $u(t-\tau)$; delay $\tau \approx 0.5$ µs
- u is combined with dc voltage V_S

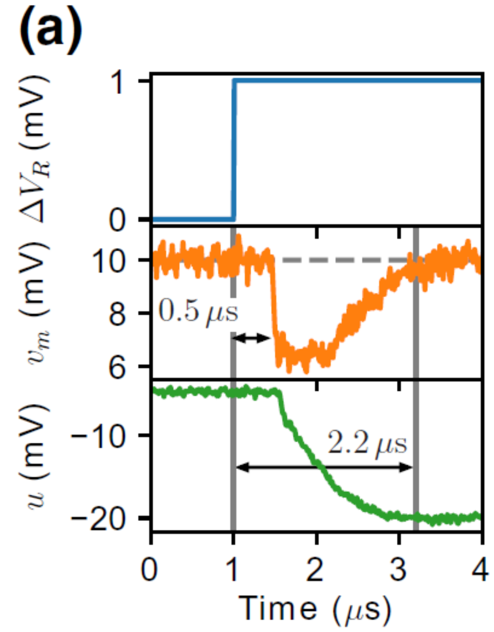


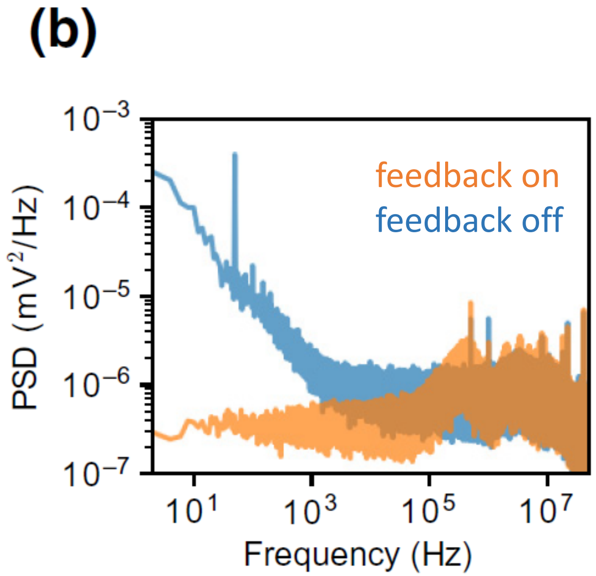
Characterization of the feedback control

(a): - Keysight M3300A digitizer has I/O latency of $0.5\ \mu s$
- Total settling time in u of $2.2\ \mu s$ (not optimized to avoid instability)

(b): - Noise power spectral density of v_m: $1/f$ tail is suppressed by feedback control (up to $\approx 100\ kHz$)

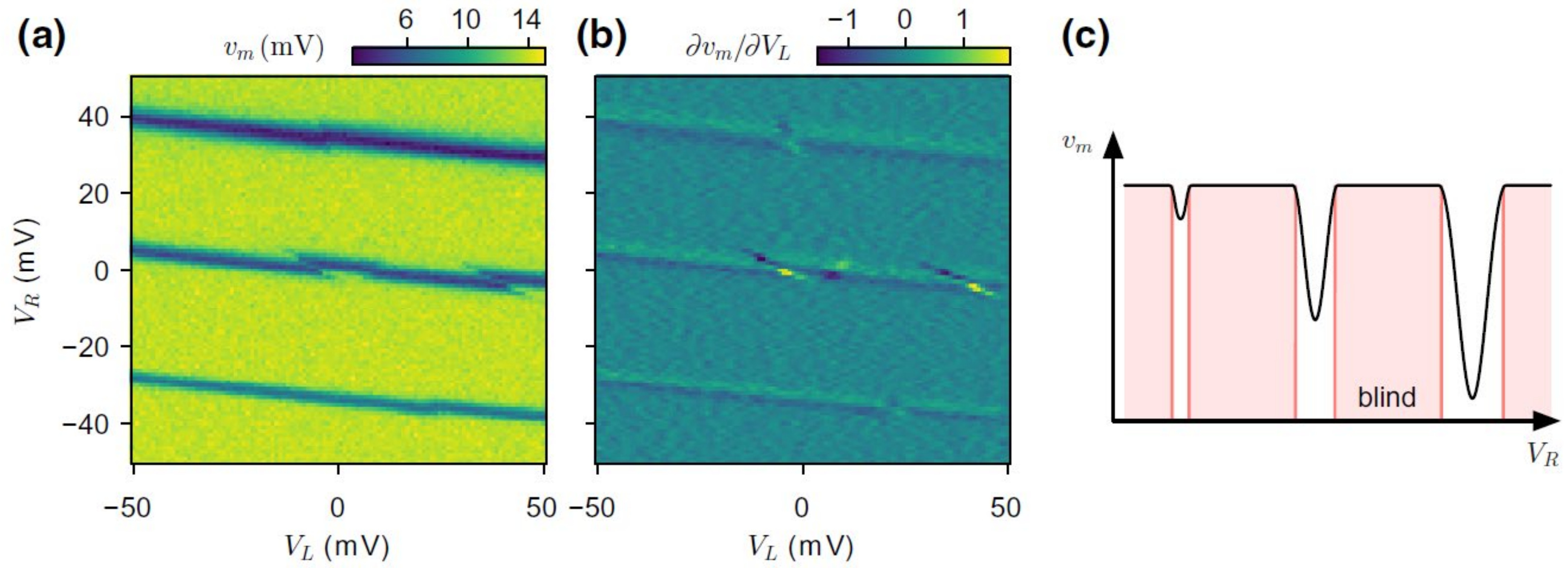






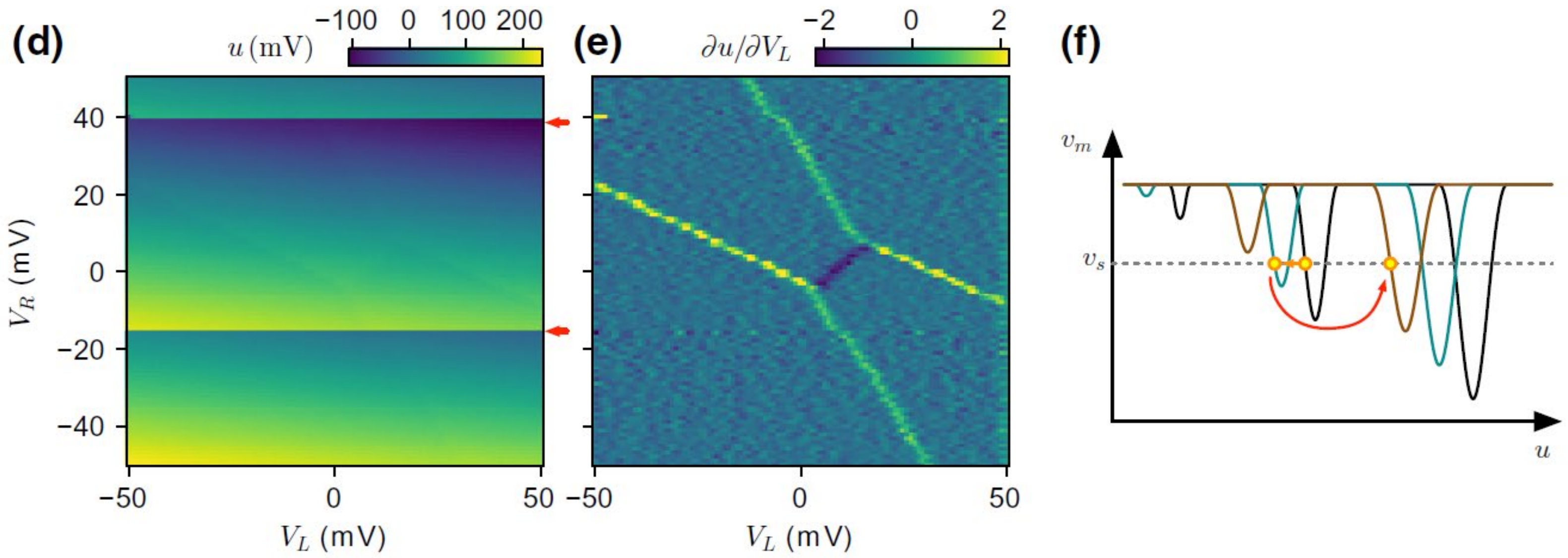
Charge stability diagrams (feedback loop off)

- Operating window of charge sensor is narrower when operated in few-electron regime for enhanced sensitivity
- Demodulated rf-signal v_m shown in (a) and its derivative in (b)
- Sensor is sensitive only near the Coulomb peaks, mostly blind in Coulomb blockade regime



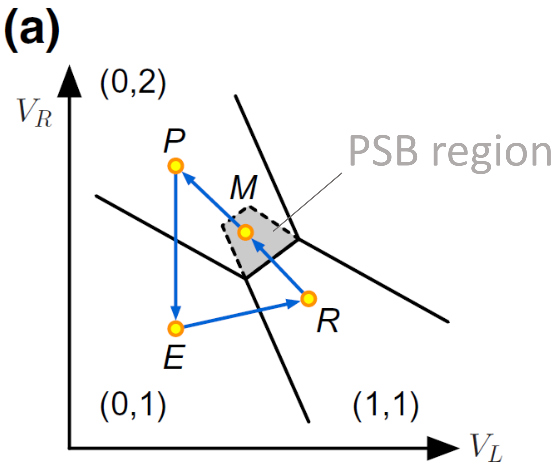
Charge stability diagrams (feedback loop on)

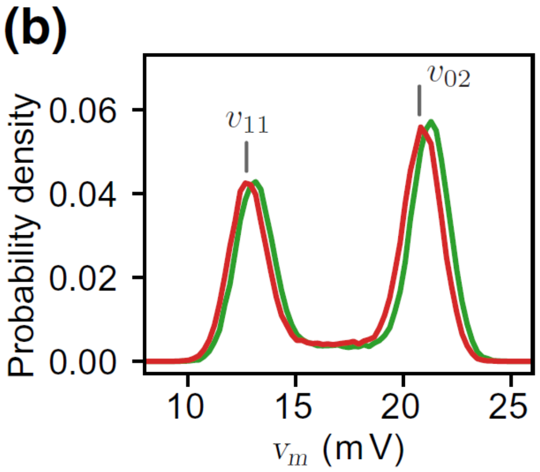
- Control voltage u shown in (d) and its derivative in (e)
- PID control is reset at t=0 in lower left corner of scan
- Red arrows: Jump from one Coulomb peak to another in the charge sensor
- Yellow circles in (f): Points towards which u is controlled to fulfill $v_m = v_s$
- As V_R is increased, signal trace shifts to the left (black->green->brown)



Single-shot spin measurement (I)

- Pulse cycle (a): **E**mptying->**R**eloading->**M**easuring->**P**arking->**E**mptying->…
- Dwell times $10\ \mu s\ (E), 10\ \mu s\ (R), 445\ \mu s\ (M), 35\ \mu s\ (P)$
- Outcomes $v_m = v_{11}$ (triplet) and $v_m = v_{02}$ (singlet)
- Histogram in (b): PID control disabled, 100'000 measurements, $t_{int} = 5\ \mu s$
- v_{11} and v_{02} fluctuate due to first-order drift of charge sensor and $v_{02} - v_{11}$ fluctuates due to second order drift → broadening of histograms





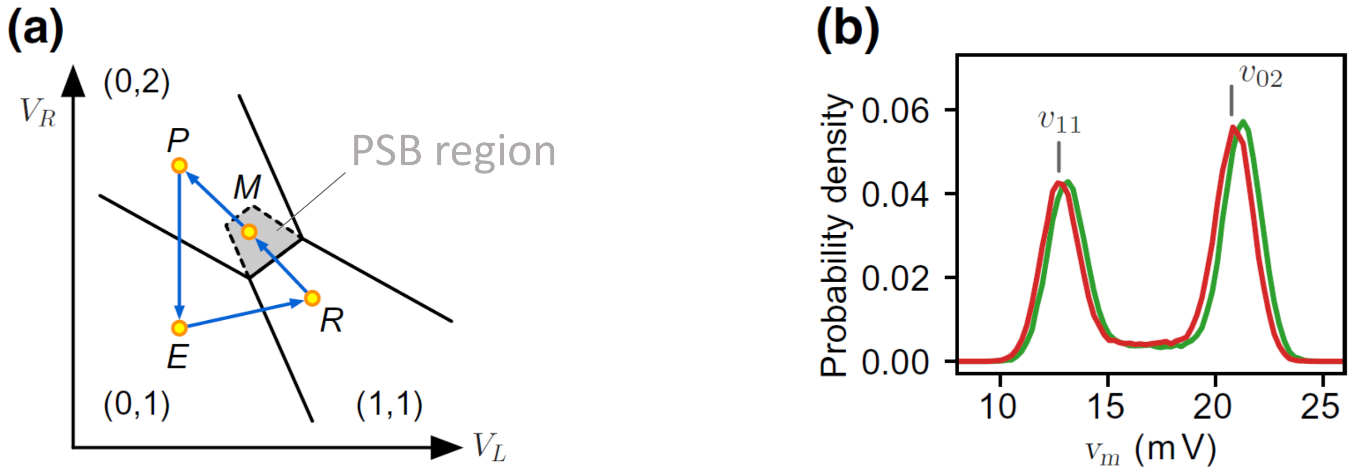
Single-shot spin measurement (II)

- In principle, one could turn on the PID control continuously and measure u, but this has a few drawbacks:

  → Settling time of u ($\approx 2.2\ \mu s$) is an order of magnitude longer than shortest single-shot measurement time achievable in similar setup [1]

  → Application of control pulses may cause failure of the feedback loop

- Instead, activate PID control only at point **P** to stabilize charge sensor

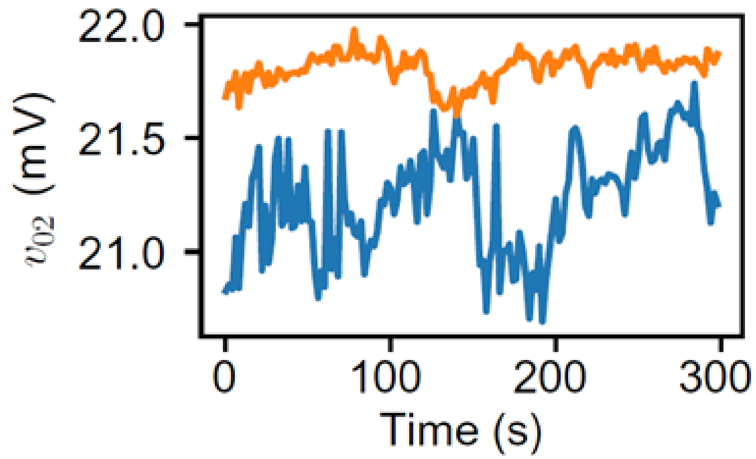


[1] C. Barthel et al., Phys. Rev. B 81 (2010)

Single-shot spin measurement (III)

- Activate PID control only at point **P** to stabilize charge sensor:

  → Fluctuation of v_{02} over time is successfully suppressed



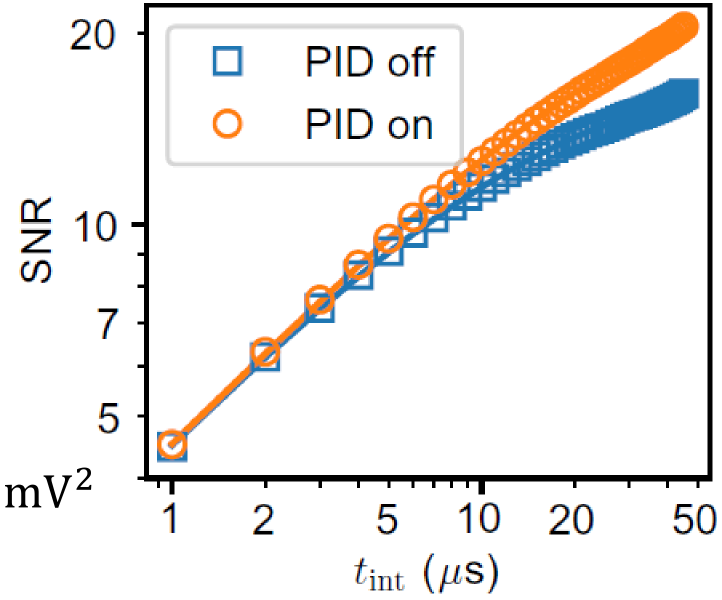
Single-shot spin measurement (IV)

- Activate PID control only at point **P** to stabilize charge sensor:

→ Noise suppression improves signal-to-noise ratio SNR = $|v_{02}-v_{11}|/\sigma$
(σ^2: variance of each peak in histogram)

→ SNR is fitted to: $\sigma = \sqrt{\sigma_0^2/[t_{\mathrm{int}} + t_0] + \sigma_d^2(t_{\mathrm{acq}})}$

(σ_0^2: white-noise broadening)
(σ_d^2: low-frequency noise contribution)
(t_0: measurement bandwidth)



→ For acquisition time $t_{acq} = 300$ s:
PID off: SNR saturates for longer t_{int}, with $\sigma_d = 0.2\ \mathrm{mV}^2$
PID on: SNR improves, and $\sigma_d = 0.1\ \mathrm{mV}^2$

→ Reduction of σ_d has larger impact on readout fidelity for smaller SNR:
Example: $|v_{02}-v_{11}| = 2$ mV, $t_{int} = 100$ µs; Readout error is 1.9% for $t_{acq} = 300$ s, 3.5% for $t_{acq} = 24\ h$ with PID off, 0.3% with PID on

Summary

- Charge sensor is maintained in sensitive spot by using a feedback loop
- Settling time $\approx 2.2\ \mu\mathrm{s}$ allows for suppression of noise below $\approx 100\ \mathrm{kHz}$
- Demonstration of improved charge stability diagram measurements and single-shot spin readout
- Feedback control may be particularly useful for tasks with longer calculation time, larger qubit systems