Characterisation of the Copenhagen Board

End of Project Presentation

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SQA Summer Research Scholarship

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Outline

Aim

- To characterise the RF operation of the Copenhagen board
- To perform RF reflectometry on a transistor connected to the board
- To optimise the resonance circuit for resistance matching

Copenhagen Board

The Copenhagen Board (CPH) allows for connections to a device via both DC and high-frequency circuitry, with spaces for additions of resistors, capacitors, and inductors.

- Manufactured by QDEV
- Specially designed for quantum devices
- 50 DC lines
- 16 AC lines (up to 18GHz)
- 4 multiplexed LC tank circuits

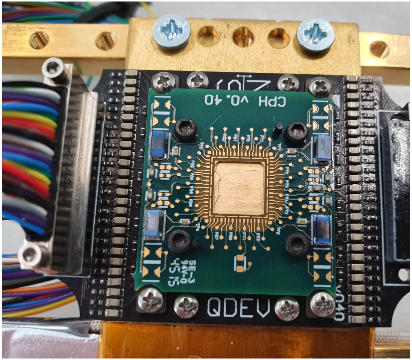


Figure 1: Copenhagen motherboard (black) and daughter board (green).

Copenhagen Board

- Although CPH has been used for DC measurements, its usage under RF AC measurements is unfamiliar
- RF measurements can be beneficial because they allow for larger bandwidth (faster timescales) and lower $1/f$ noise
- Characterisation of the board involves understanding its circuitry, resonance, and the role of the inductors, capacitors, and resistors

MOSFET Transistor

- To characterise the CPH board, a transistor can be used as a placeholder for more complex quantum devices
- The transistor is a MOSFET - a *metal oxide semiconductor field-effect transistor*

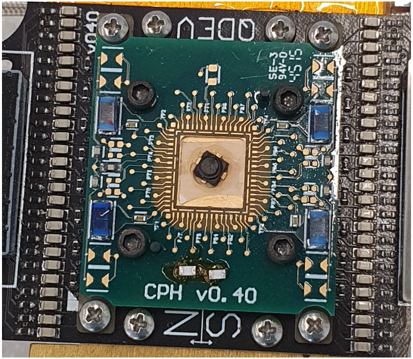


Figure 2: Transistor (black square in the gold) bonded to the daughter board.

Transistor Characterisation

- First need to determine if the transistor is operating correctly
- 4-wire sensing was used to isolate the resistance of the transistor
- The CPH board included $\sim 7.4\text{k}\Omega$ resistors in series

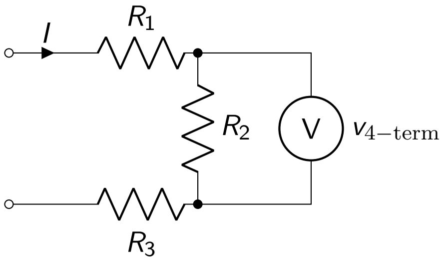


Figure 3: 4-wire resistance sensing to determine $R_2 = v_{4-\mathrm{term}}/I$.

Results - 4-wire Sensing

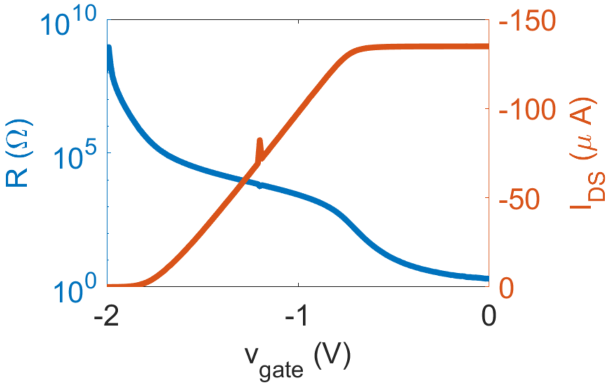


Figure 4: Current and resistance of the transistor as a function of gate voltage. Drain-source voltage is held constant at $v_{DS} = -1$V.

Results - 4-wire Sensing

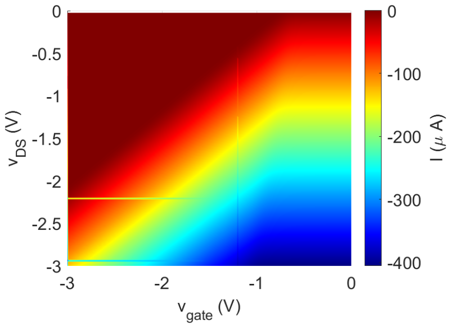


Figure 5: Current through the transistor as a map of drain-source and gate voltages.

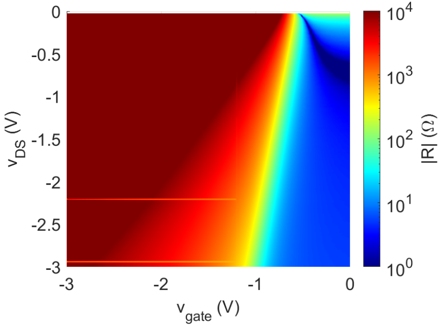


Figure 6: Resistance of the transistor, using 4-wire sensing

RF Reflectometry

- Reflectometry allows us to probe the resistance of the transistor
- RF signals are inputted and reflected power is given by the following:

$$Z_t = i\omega L + \frac{1}{\frac{1}{R} + i\omega C_p} \quad (1)$$

$$\Gamma = \frac{Z_t - Z_0}{Z_t + Z_0} \quad (2)$$

$$S11 = |\Gamma|^2 \quad (3)$$

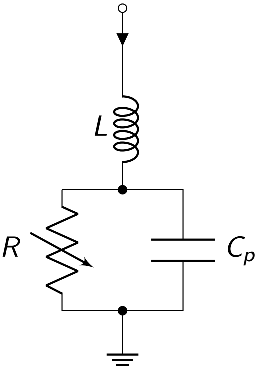


Figure 7: RLC circuit for RF reflectometry.

RF Reflectometry

An inital RF-sweep without bonds to the transistor shows resonant peaks at frequencies corresponding to the four inductors:

Inductor	f_{res} (MHz)	L (nH)	C_p (pF)	Status
$L1$	164	1200	0.79	-
$L2$	192	820	0.84	-
$L3$	186	560	1.3	Gate
$L4$	50	390	26	Source

Table 1: Measured resonant frequencies for each inductor on the Copenhagen board; Parasitic capacitance calculated using $f_{\mathrm{res}} = 1/2\pi\sqrt{LC_p}$.

RF Reflectometry Simulations

Using $L = 390\text{nH}$, $C_p = 26\text{pF}$, we simulate theoretical reflectance using Equation 3:

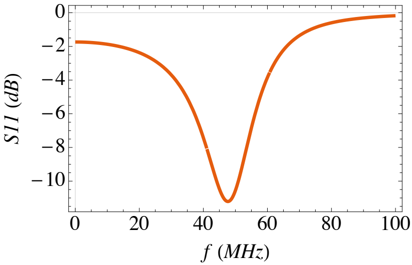


Figure 8: Simulated resonance peak at $R = 1\text{k}\Omega$ and $C_p = 26\text{pF}$. Resonance occurs at $f \approx 48\text{MHz}$.

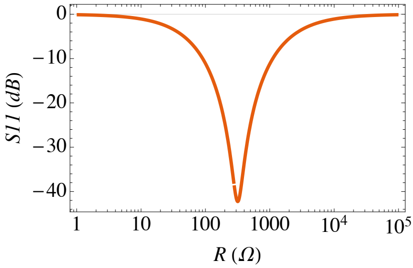


Figure 9: Simulated transfer function at resonant frequency.

RF Reflectometry Measurements

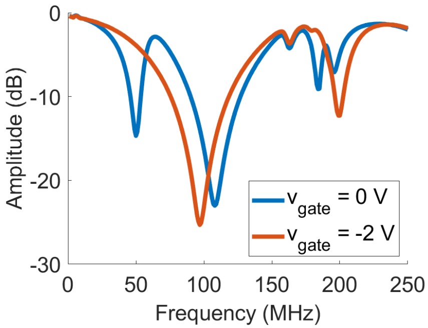


Figure 10: Resonance peaks at different gate voltages.

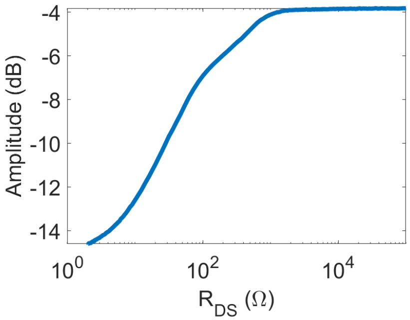


Figure 11: Transfer function at $f = 50\text{MHz}$ and $v_{DS} = -1\text{V}$.

Improved simulation model

The simple RLC circuit is not a precise representation of the actual CPH circuit; instead, the RF signal follows a path more akin to:

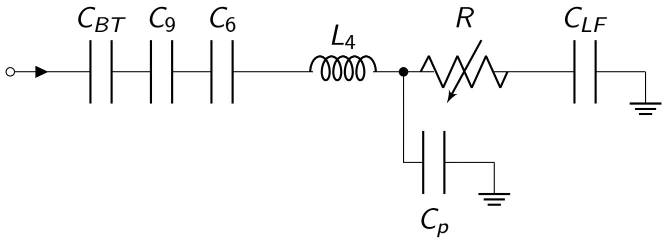


Figure 12: More accurate circuit diagram for the resonance circuit, with the transistor modelled as a variable resistor.

Improved simulation model

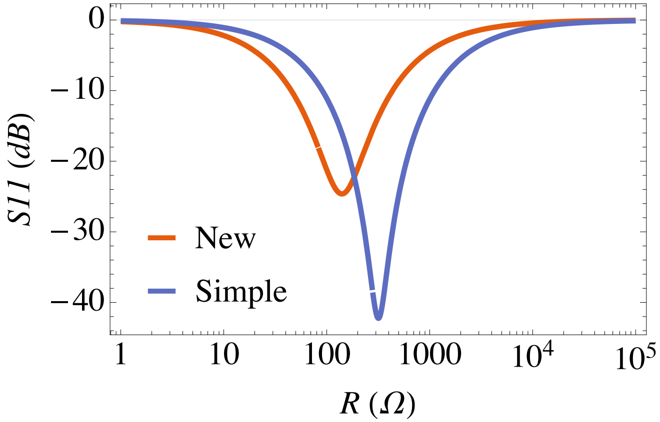


Figure 13: Transfer function comparison between the model from Figure 12 and that in Figure 9.

Optimisation using Shunt Capacitors

- One issue could be that the matching resistance is too low
- By adding a shunt capacitor in parallel, we should be able to shift the matching resistance

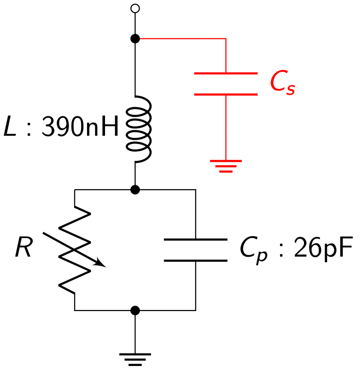


Figure 14: Circuit diagram for optimised RF reflectometry circuit.

Simulations with Shunt Capacitors

The impedance of the new circuit (Figure 14) should be:

$$Z_t = \left[\left(i\omega L + \frac{1}{\frac{1}{R} + i\omega C_p}\right)^{-1} + i\omega C_s\right]^{-1} \tag{4}$$

This can then be applied to Equation 3 to simulate the effects of a shunt capacitor.

Simulations with Shunt Capacitors

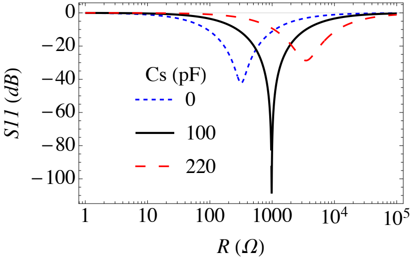


Figure 15: Comparison of transfer functions with shunt capacitors.

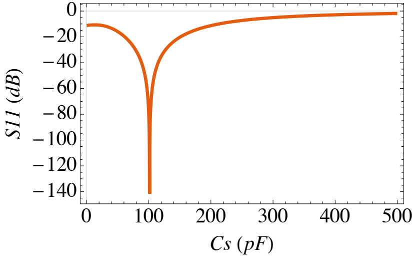


Figure 16: Simulation of S11 values as a function of the included shunt capacitance, at a fixed value of $R = 1\text{k}\Omega$.

RF Reflectometry With A Shunt Capacitor

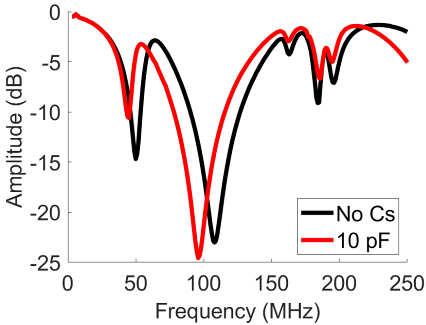


Figure 17: Resonance peaks with $C_s = 10\text{pF}$ and $C_s = 0$, holding $v_{DS} = -1\text{V}$, $v_{\text{gate}} = 0$.

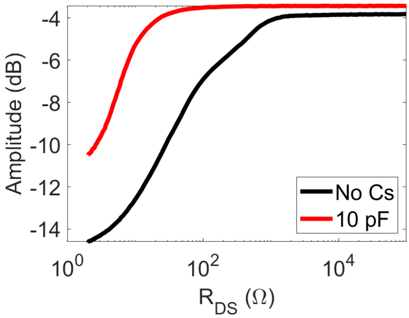


Figure 18: Transfer function at $f = 44\text{MHz}$ with $C_s = 10\text{pF}$ and at $f = 50\text{MHz}$ with $C_s = 0$.

RF Reflectometry With a Shunt Capacitor

- When a $C_s = 220$pF and a $C_s = 1$nF capacitor were used, no resonance peaks were observed

This may be due to:

- At larger values of C_s, the impedance of the capacitor is lower than the RLC circuit
- This creates an RF path to ground, bypassing any resonance that may occur

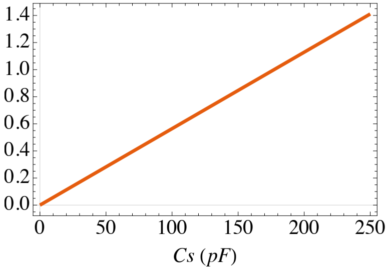


Figure 19: Ratio of RLC impedance to C_s impedance as a function of C_s, at $f = 50$MHz.

Variable Capacitors

- Attempted to incorporate a variable shunt capacitor onto the CPH daughter board with the transistor
- Also attempted with a new silicon MOSFET device with smaller C_p and larger R
- However was unable to measure the effective capacitance and resonance due to equipment difficulties

Future Directions

- Beneficial to compare impedances on a device known to respond to shunt capacitances
- Repeat methods with a 100nF capacitor (the theoretical optimum)

4K Testing of Germanium Quantum Dot

Gate tested *BB4* (germanium quantum dot) at 4K to check that all the gates and ohmics work correctly.

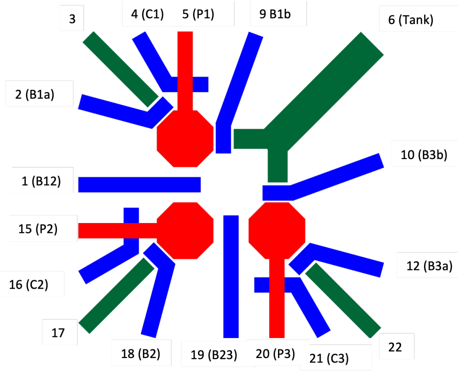


Figure 20: Schematic diagram of the gates on the device; green - ohmics; blue - barrier electrodes; red - plunger electrodes

Other Subprojects

- Tested all contacts on two CPH boards
- Updated AWG Pulse Studio for MATLAB v2 and implemented a parametric function option
- Updated VNA driver for MATLAB v2
- Created a driver for the Keithley SM2401 source meter in MATLAB v2
- Created a driver for the Yokogawa IM7651 Variable DC Source in MATLAB v2

Thank you!

Appendix

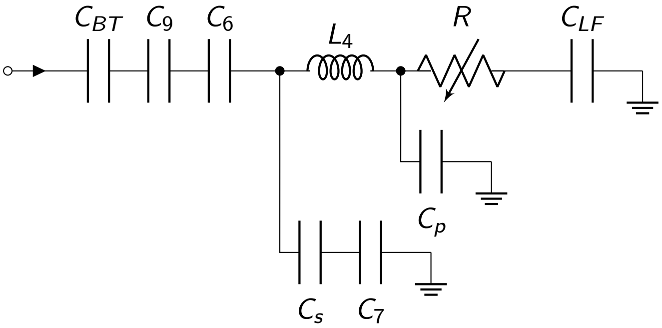


Figure 21: Figure 12 with added shunt capacitor.

Appendix

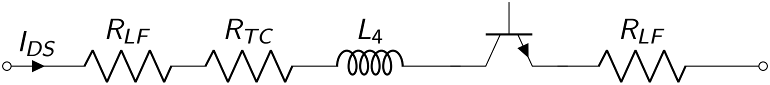
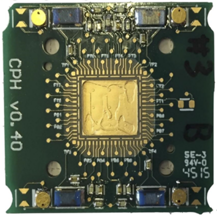


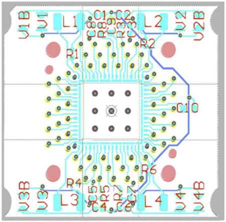
Figure 22: DC circuit supplying the transistor.

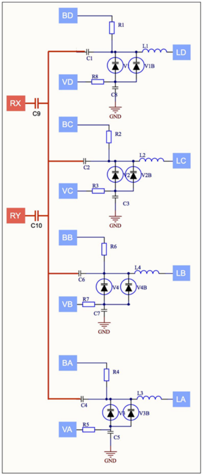
Appendix

Copenhagen daughter board "CPH v0.40":



Definition of labels:





Resonance Maps

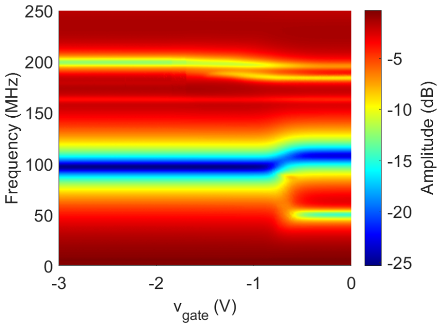


Figure 23: Resonance peaks at various v_{gate}, without a shunt capacitor.

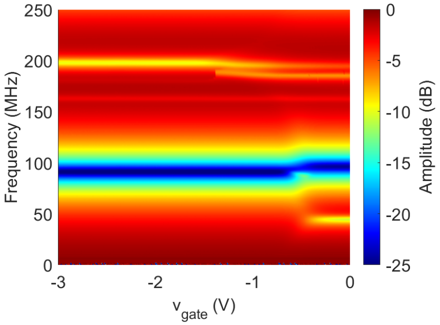


Figure 24: Resonance peaks at various v_{gate}, with $C_s = 10\text{pF}$.

Transfer Functions

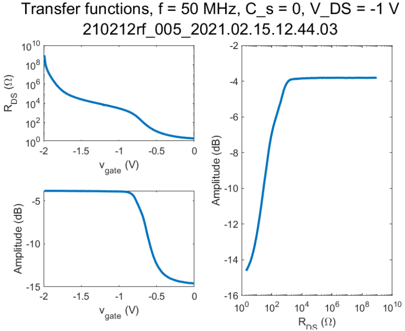


Figure 25: Transfer function at $f = 50\text{MHz}$ and $v_{DS} = -1\text{V}$, with no shunt capacitor

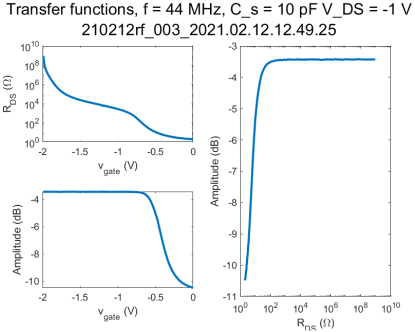


Figure 26: Transfer function at $f = 44\text{MHz}$, with $C_s = 10\text{pF}$.