Hybrid simulation of the RF-SETs and their charge sensitivity analysis

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1. Introduction

In principle, the single electron transistor (SET) can be used as a near-quantum limited amplifier because of its high charge sensitivity [1]. But the typical SET resistance of 100kohm and the load capacitance of 1nF at the output restrict the measurement bandwidth to few kilohertz or less, which leads to the slow operating speed and *1/f* noise impairment. Rather than carrying out the conventional voltage and current measurement, radio frequency single electron transistor (RF-SET) adopts the measurement of high frequency signal reflected [2] and transmitted [3] across the SET using a tank circuit. This novel concept helps to realize the upper measurement frequency limit of 100MHz and above and a high charge sensitivity of $3.2\times10^{-6}\ e/\sqrt{Hz}$ [4].

Sensitivity of the rf-SETs depends on a number of design parameters, such as the amplitude and frequency of gate- and carrier-signals, the SET resistance etc. To realize a high sensitivity and wide bandwidth RF-SET it is necessary that the various parameters have to be chosen appropriately. In order to evaluate the effect of each parameter on RF-SET sensitivity, we have developed a simulation method for the transmission and reflection type rf-SETs. Using this simulation, we analyze the effects of the tunnel junction resistance, tank circuit matching, the interconnection loss between SET and cryogenic amplifier and the carrier signal amplitude on rf-SET sensitivity.

2. Simulation method

We have used the analytical SET model [5] implemented in smartspice [6] with Verilog-A as a subcircuit consisting of analogue behavior devices. Other components in the RF-SET are realized using the SPICE equivalent circuits. Hybrid combination of the SET analytical model and SPICE makes it possible to simulate RF-SETs. Fig. 1 shows the schematic diagram of the simulated reflection type RF-SET. In this circuit, the directional coupler is simulated using two transformers [7] to direct the reflected signal from the tank circuit towards the cryogenic amplifier and to couple the RF carrier to the tank circuit. C_{pad}, the parasitic capacitance between the contact pad and the SET, and the inductor form resonant circuit to couple the high resistance SET to a 50-ohm high frequency measurement setup. Fig. 2 shows the schematic diagram of the simulated transmission type RF-SET. SPICE equivalent circuit of the chip inductor provided by the manufactures was used to include the high frequency parasitic of chip inductor in the simulation.

Upper frequency limitation of the analytical SET model:

In our simulation, analytical model has been used within the time limitation of $t>R_\Sigma C_\Sigma$. For the SET resistance of 200Kohm and the island capacitance of 90aF, the upper frequency limit is 5.5GHz. We have done the simulation with in this upper frequency limitation.

3. Simulation results

The charge sensitivity of the RF-SET is calculated by

$$\delta q = \frac{\Delta Q}{\sqrt{RBW}\times 10^{\frac{SNR}{20}}}.$$

Where ΔQ is the value of the gate signal measured in electrons (rms), RBW is the resolution bandwidth used for the spectrum analyzer, and SNR is the signal to noise ratio for the side peak, measured in dB. In our simulation results, the gate signal amplitude and the RBW are kept as a constant and the value of SNR is used to compare the charge sensitivity for various parameters. Effect of the various parameters on the RF-SET sensitivity has been analyzed in the remaining part of this section.

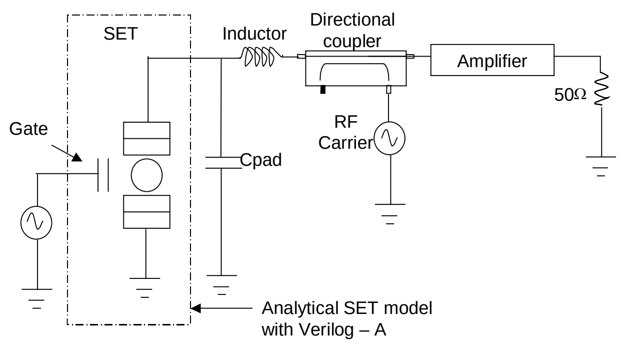

Fig. 1 Schematic diagram of the simulated reflection RF-SET circuit

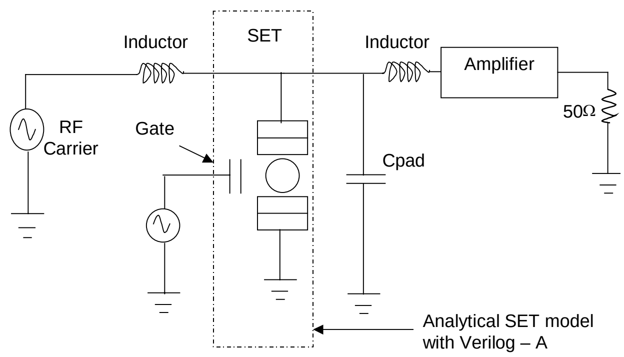

Fig. 2 Schematic diagram of the simulated transmission RF-SET circuit

3.1 Tunnel junction resistance

To estimate the dependency of the charge sensitivity on SET tunnel junction resistance we varied the tunnel junction resistance by keeping other parameters as a constant. Fig. 3 shows the variation of the SNR with tunnel junction resistance and its comparison with the analytical calculation. Simulation shows that the decrease in charge sensitivity follows a first order exponential decay. It indicates the importance of the low tunnel junction resistance SET in accomplishing high charge sensitivity RF-SET.

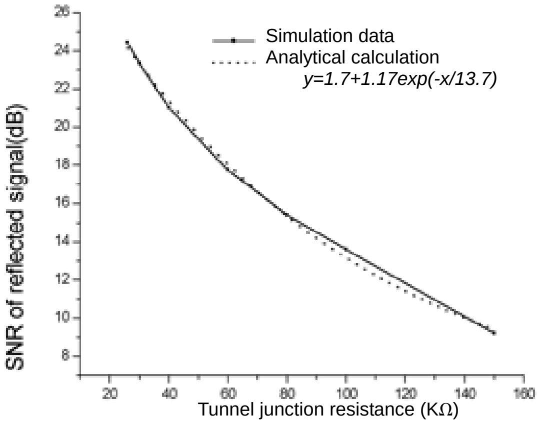

Fig. 3 Simulation of SNR for various tunnel junction resistance and comparison with analytical calculation

3.2. Tank circuit matching

Tank circuit controls the coupling between the high resistance SET and 50ohm high frequency measurement system. Fig. 4 illustrates the dependence of detected signal SNR for the various C_{pad} valves. In this simulation we kept the tank circuit inductor value as a constant and the pad capacitance value was varied. Maximum SNR is achieved for the matching condition given in the insert of the Fig. 4.

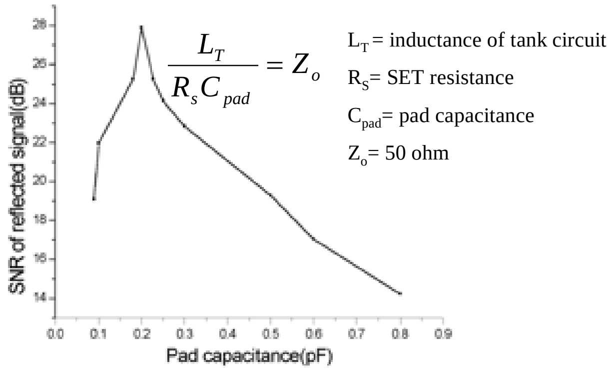

Fig. 4 Variation of SNR of the reflected signal for the various values of the pad capacitance

3.3. Interconnection loss between the SET and the cryogenic amplifier

Noise is introduced between the SET and the cryogenic amplifier interconnection due to the cable losses. This noise gets the importance because the reflected or transmitted signal from the SET is very low in amplitude. To evaluate the impact of this noise on RF-SET sensitivity, interconnection cable loss is varied and its influence on SNR is plotted in the Fig. 5. Simulation shows that the SNR linearly degrade with the interconnection losses.

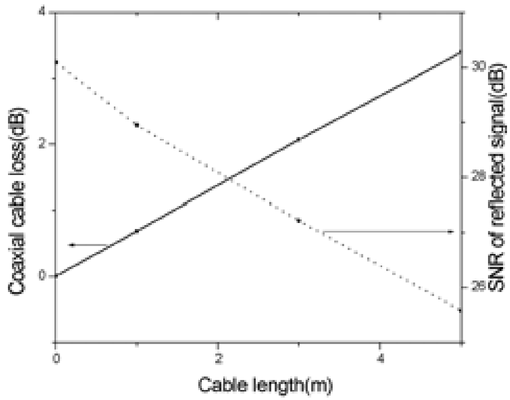

Fig. 5 Variation in SNR due to the interconnection cable loss between SET and cryogenic amplifier.

3.4. Carrier amplitude

Amplitude of the carrier has to be chosen such that it gives a maximum response. Fig. 6 depicts the simulation result for the carrier amplitude variation**.** For the normal state SET, the carrier amplitude of E_c/e (E_c -Charging energy of the SET) gives maximum charge sensitivity.

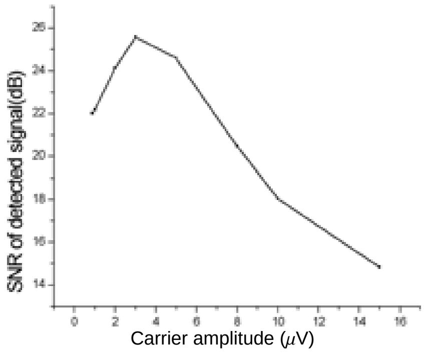

Fig. 6 Variation of SNR for the different carrier signal amplitude values.

4. Conclusion

We have developed the RF-SET simulation method by combining of the SET analytical model and SPICE. Using this simulation method, the effect of various parameters on RF-SET charge sensitivity has been analyzed. To realize a high charge sensitivity RF-SET, optimal selection among the various design parameters is important.

References

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