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CAS

Silicon Spin Qubit Control and Readout Circuits in 22nm FDSOI CMOS

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Outline

- Silicon-based monolithic quantum processor
  - EU H2020 FET Open project **IQubits**
- Silicon electron/hole spin qubits
- Qubit control and readout techniques
- Qubit ICs
- Conclusions

Si-based quantum processors

- Quantum supremacy
  - Promises disruption
  - Requires highly-scalable quantum processors

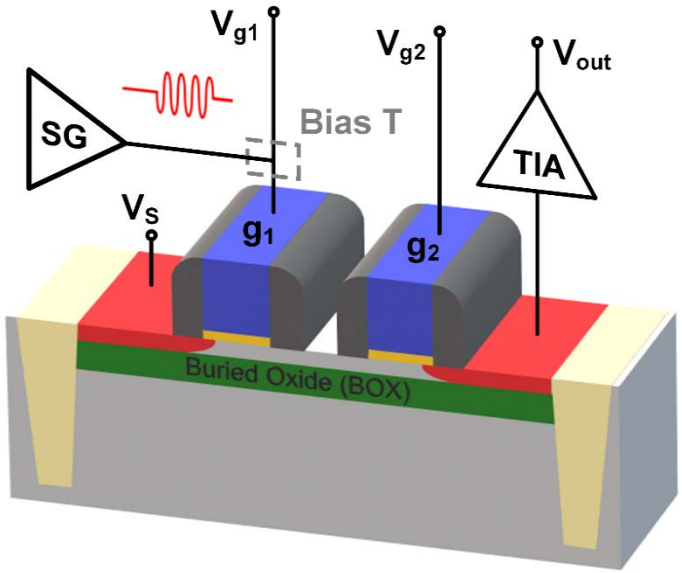
- Early-stage approaches (multi-chip)
  - Quantum chip (**T < 100 mK**)
  - Classical chip for control and readout (**T ~ 4 K**)
  - Bulky instrumentation
  - Bulky interconnects

⇒ **Not scalable**

Si-based monolithic quantum processor: EU H2020 project IQubits

- Building blocks for highly-scalable quantum processor in ultra-scaled (22nm and below) FDSOI CMOS foundry techs
  - **Electron/hole-spin qubits operating at T ≥ 3 K**
  - **Co-integration of qubits with control and readout (RO) circuits**
  - **www.iqubits.eu**

- Here we address the preliminary design and considerations
  - Signal generator (SG)
  - Transimpedance amplifier (TIA)

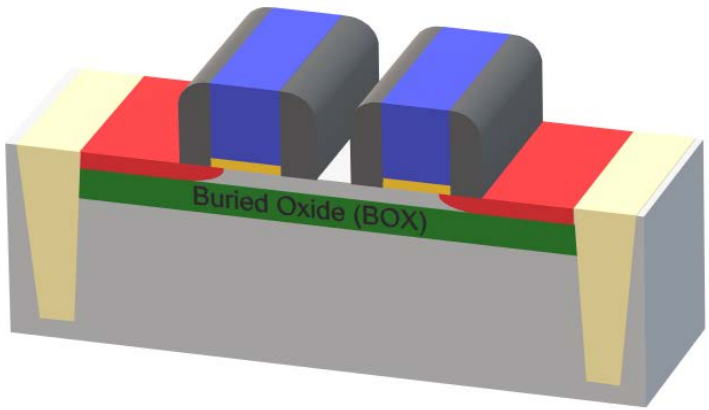


[S. Bonen et al., IEEE EDL, 2019]

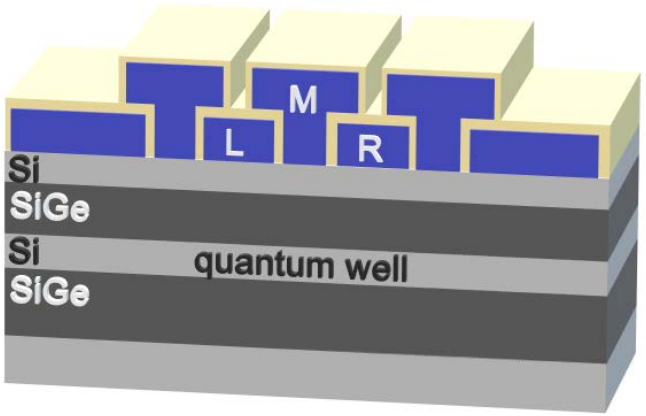
Silicon electron/hole spin qubits

- Advantages
  - **Long coherence time (isotopically-purified Si)**
  - **Compatibility with IC manufacturing techs for high-scalability**

- Implementations of double quantum dots (DQDs)



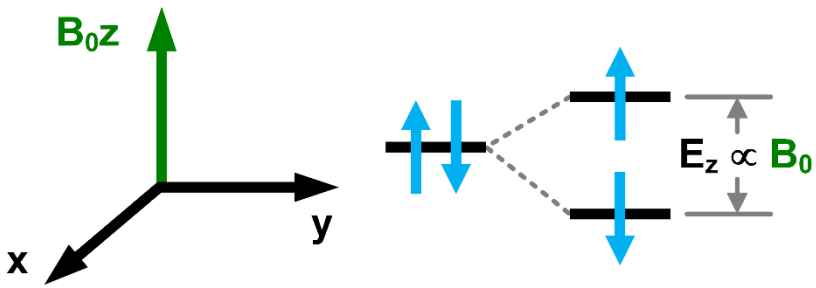
[R. Maurand et al., Nature Commun., 2016]
[S. Bonen et al., IEEE EDL, 2019]



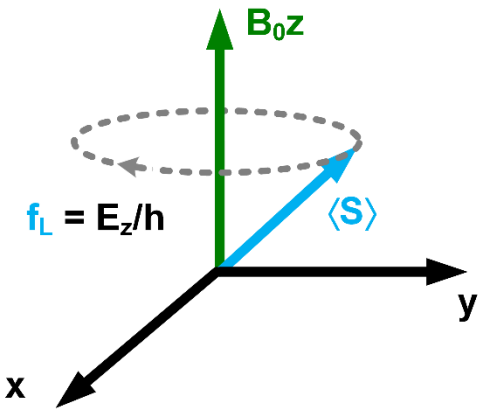
[D.M. Zajac et al., Science, 2018]

Qubit Control & RO: Magnetic field effect on spin (1/2)

- Zeeman splitting of spin states
  - Static field $B_0\hat{z}$ lifts degeneracy
  - Energy separation $E_Z \propto B_0$
  - Spin precession about z-axis with Larmor frequency $f_L = E_Z/h$



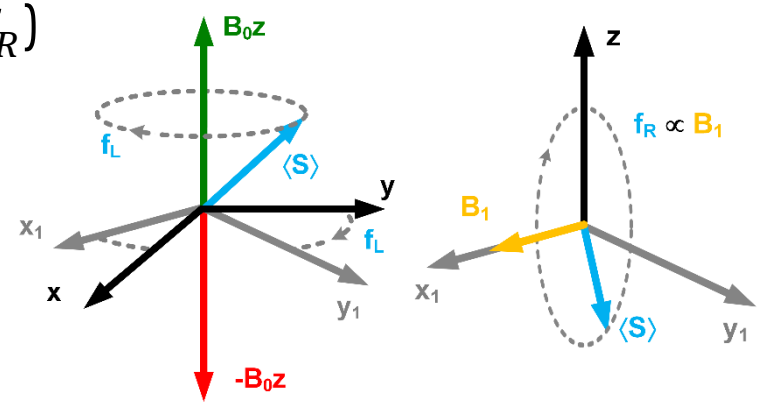
Zeeman effect



Spin precession

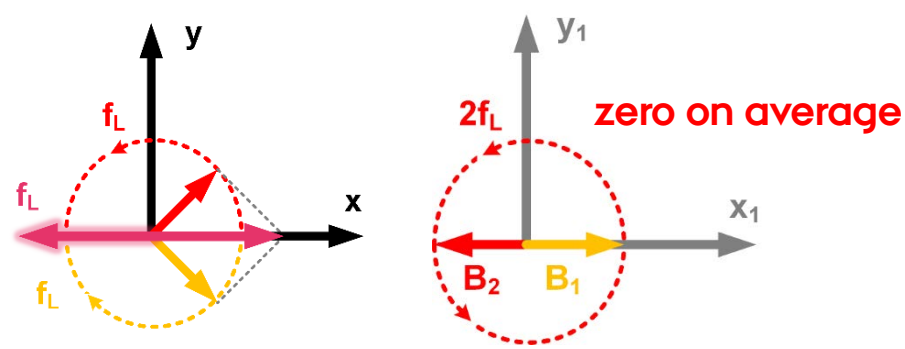
Qubit Control & RO: Magnetic field effect on spin (2/2)

- Rabi oscillations
  - Magnetic field $\boldsymbol{B_1(t)}$ rotating at f_L in xy-plane (perturbation)
    ⇒ spin-up probability varies periodically with duration time
  - Freq. of oscillations: Rabi frequency (f_R)



Rotating frame x_1y_1z

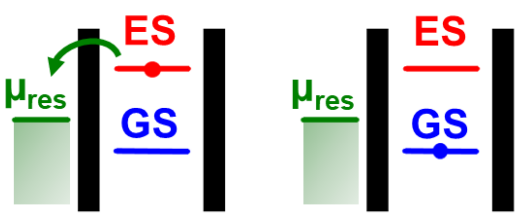
- Rotating wave approximation (RWA)
  - Rotating field approximated by oscillating field $\boldsymbol{B(t)}$
  - Requires $f_R \ll f_L$



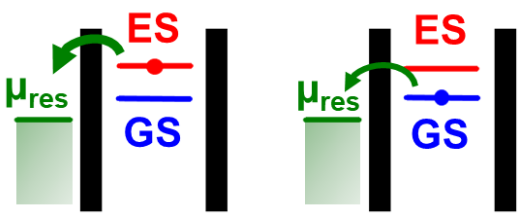
$B(t) = B_1(t) + B_2(t)$

Qubit Control & RO: Spin manipulation & RO techniques

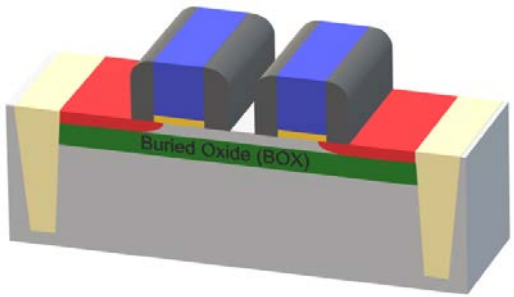
- Spin manipulation
  - Electron-spin resonance (ESR): $B(t) \propto I(t)$
  - Electric dipole-spin resonance (EDSR): $B(t) \propto V(t)$
- RO
  - Energy-selective (ERO)
  - Tunnel-rate-selective (TR-RO)
  - Spin blockade + charge sensor
  - Gate reflectometry



ERO



TR-RO



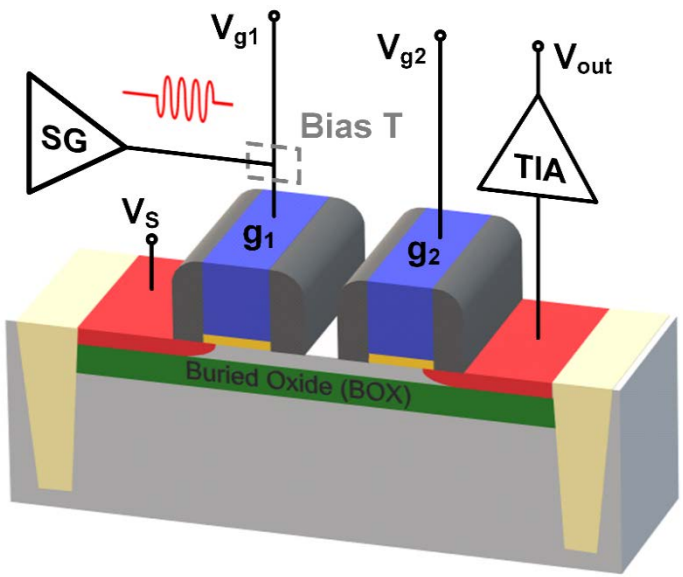
DQD

ES: Excited state GS: Ground state μ_{res}: Electrochemical potential of reservoir

Monolithic qubit ICs: Performance considerations

- Qubit operation at 3 K
  - $E_Z = k_B T \simeq 0.25$ meV
  - $f_L \simeq 60$ GHz
- TIA
  - Expected tunneling currents ~ 10 pA - 10 nA
  - $V_{out} \sim 1$ mV on 50Ω test equipment (experimental proof)
  - Transimpedance gain: 100-140 dBΩ
- SG
  - Voltage-controlled oscillator (VCO)
  - Phase noise (PN) affects fidelity

Fidelity: Measures how well a physical system implements a quantum gate



[S. Bonen et al., IEEE EDL, 2019; M.J. Gong et al., IEEE RFIC, 2019]

Monolithic qubit ICs: Fidelity considerations

- $\pi/2$ rotation gate
- Fidelity limited by RWA
  - $99.9\% \Rightarrow f_R = f_L/80 = 750\ MHz$
  - $99.3\% \Rightarrow f_R = f_L/5 = 12\ GHz$
- We estimated PN required for target infidelity of 125×10^{-6}

f_R	T_p	PN^1	Δt
$750\ MHz$	330 ps	$-74\ dBc/Hz$	4.7 ps
$12\ GHz$	20 ps	$-62\ dBc/Hz$	280 fs

[1]At 1MHz frequency offset from f_L

T_p: pulse duration

Δt: uncertainty of T_p

[J.P.G. van Dijk et al., Physical Review Applied, 2016]

Monolithic qubit ICs: Design approach

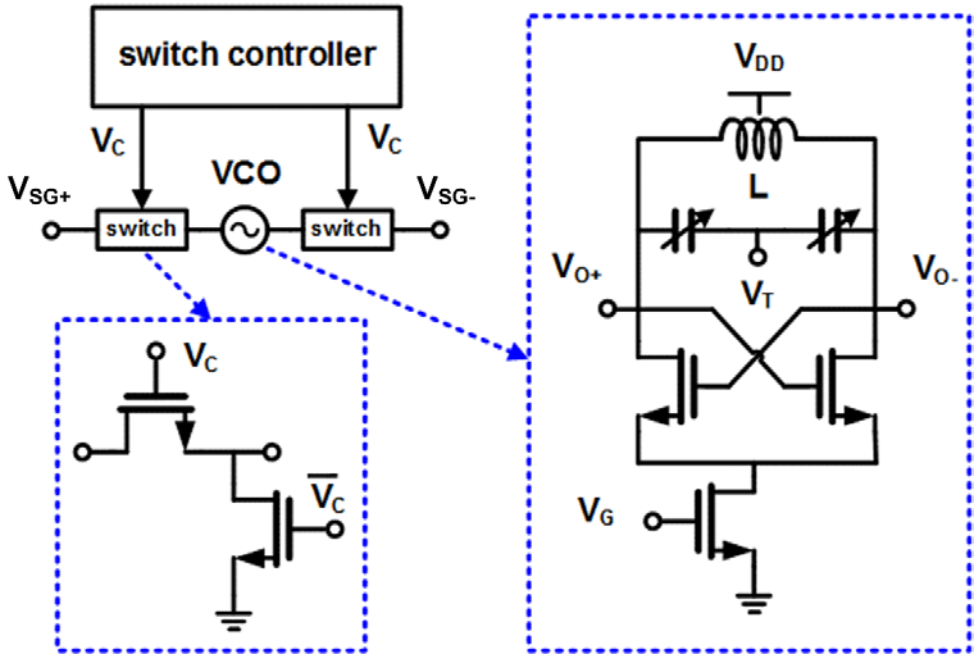
- Cryo characterization of 22nm FDSOI CMOS down to 3.3 K
  - Peak g_m of n- and p-MOSFET improves
  - Peak-f_T & peak-f_{max} current densities nearly constant
  - Passive devices exhibit lower losses
  - Normalized g_m nearly constant below 77 K

- Circuits designed at 300 K and analyzed down to 77 K
  - Simulation convergence
  - Accurate models
  - Similar or better performance expected at 3 K

[S. Bonen et al., IEEE EDL, 2019]
[M.J. Gong et al., IEEE RFIC, 2019]

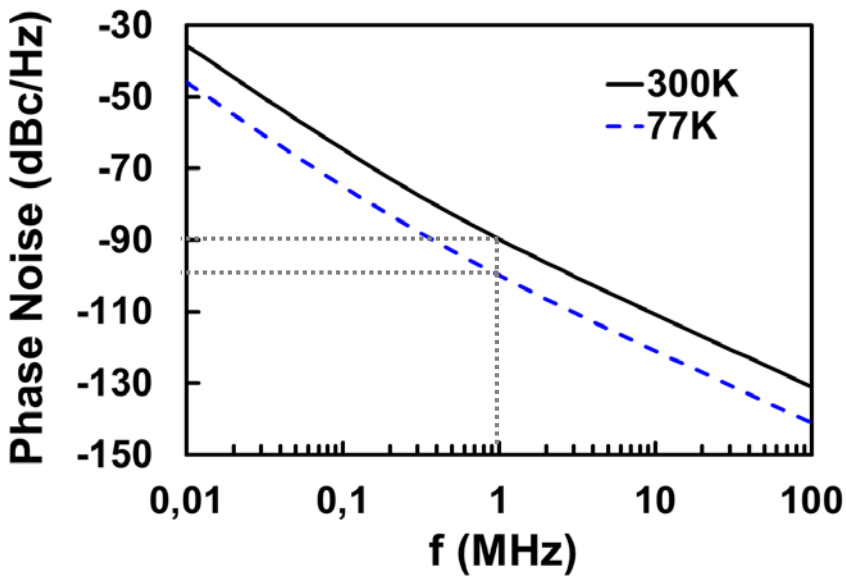
Monolithic qubit ICs: Signal generator (SG)

- VCO settling time ≃ 200 ps (**too long wrt T_p of 20 ps**)
- **SG based on 60-GHz VCO with on/off amplitude modulation**



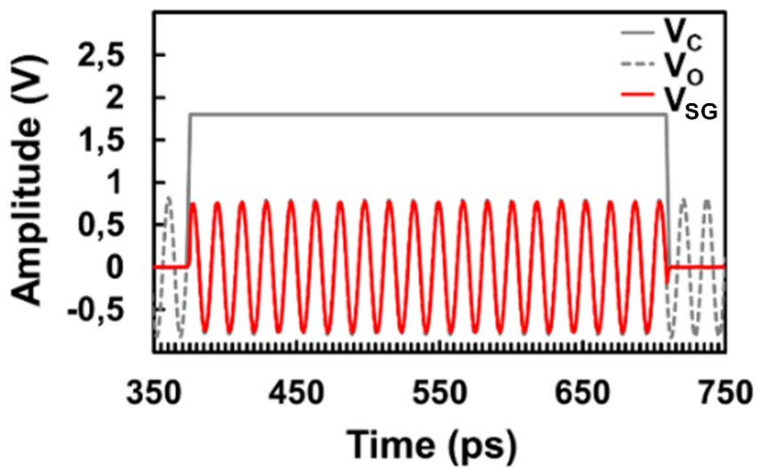
- **VCO in steady state and on/off mm-wave switches to transfer the Larmor frequency (f_L) carrier to the DQD control gate**

Monolithic qubit ICs: PN of VCO

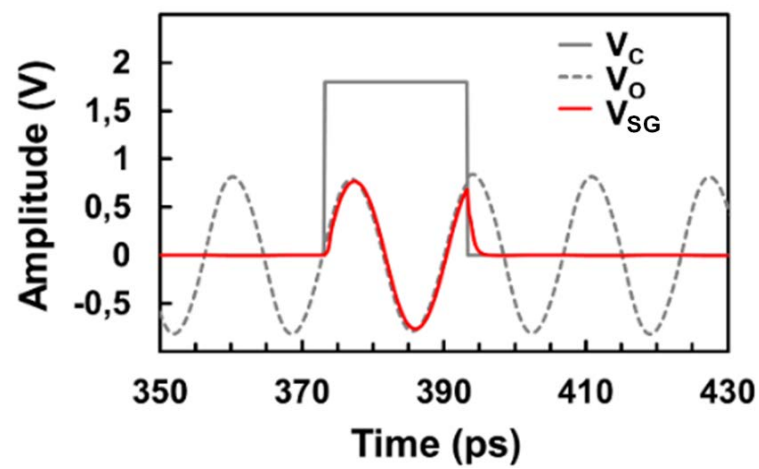


- PN at 1MHz frequency offset from 60GHz carrier
  - **-90 dBc/Hz at T = 300 K**
  - **-100 dBc/Hz at T = 77 K**
- **VCO PN well below -62 and -74 dBc/Hz emerging from fidelity considerations**

Monolithic qubit ICs: SG output signal



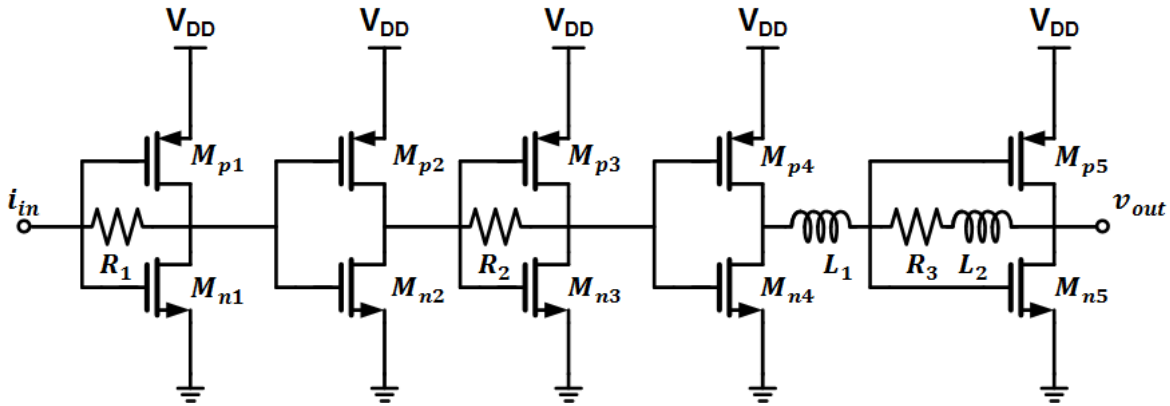
330ps π/2 pulse for $f_R = 750$ MHz



20ps π/2 pulse for $f_R = 12$ GHz

- Rise and fall times of V_C set equal to Δt/2
- Output voltage (V_{SG}) of SG generated correctly
- Pulses are slightly longer due to switch non-idealities

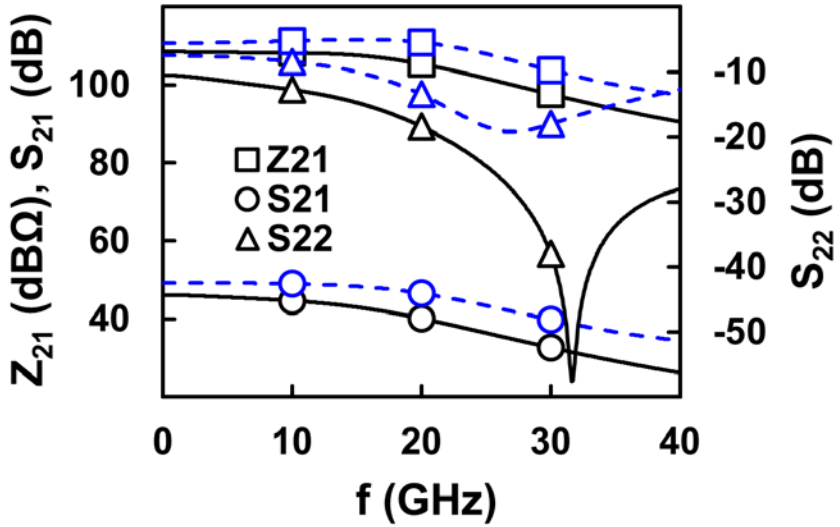
Monolithic qubit ICs: Transimpedance amplifier (TIA)

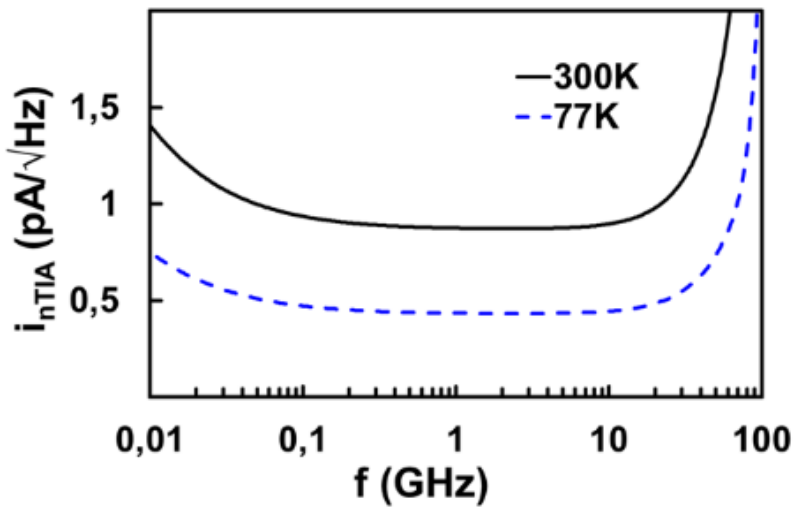


- Circuit topology
  - Mutuated from [M.J. Gong et al., IEEE RFIC, 2019]
  - But here only two inductors of 400 pH ⇒ **Higher scalability**
- Transistors biased at peak-f_{max} current density
- Input-stage MOSFETs sized for minimum input-referred noise-current spectral density (i_{nTIA})

Monolithic qubit ICs: TIA performance

- Simulation results at **300 K** (**black**) and **77 K** (**blue**)





$T\ (K)$	$P_C(mW)$	$Z_{21}(dB\Omega)$	$BW(GHz)$	$i_{nTIA}(pA/\sqrt{Hz})$
300	4.9	108	18	0.89
77	5.5	111	25	0.44

Conclusions

- Summary of techniques for control and RO of electron/hole spin qubits
- Preliminary design of SG and TIA in 22nm FDSOI CMOS tech
- SG
  - 60GHz sinusoidal pulses for $\pi/2$ rotation gates with f_R up to 12 GHz and min T_p of 20 ps
- TIA
  - Z_{21} of 108 dBΩ, 3dB BW of 18 GHz, i_{nTIA} of 0.89 pA/√Hz at 300 K
- Future works
  - Physical implementation
  - Experimental verifications down to 3 K

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