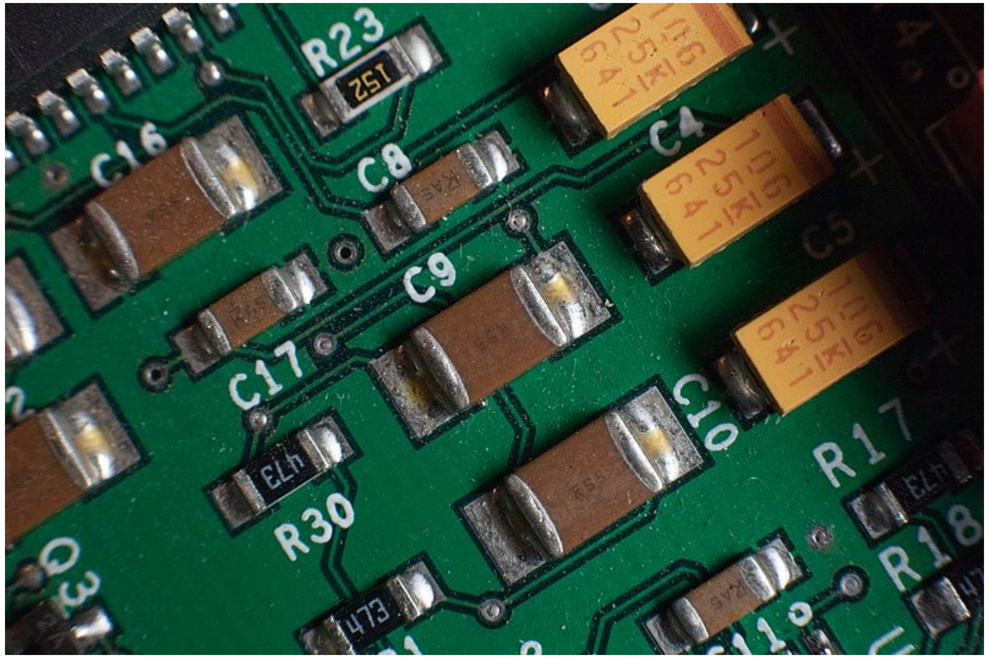
Magnon Spin Capacitor

Pieter M. Gunnink, Tim Ludwig, and Rembert A. Duine

Appl. Phys. Lett. **124**, 182404 (2024)

Motivation: the electrical Capacitor

- Widely used in integrated circuits (ICs) for manipulation in **frequency** domain (signal decoupling, high and low pass filters, etc.)
- Spintronics therefore likely require a **“spin capacitor”**
- Current proposals are either:
  - Spin polarized electrical capacitors or magnetic tunnel junction -> short spin decoherence times [1-3]
  - Storing spins over long times -> no *fast* responses [4]
- Can **magnons** fill this niche?

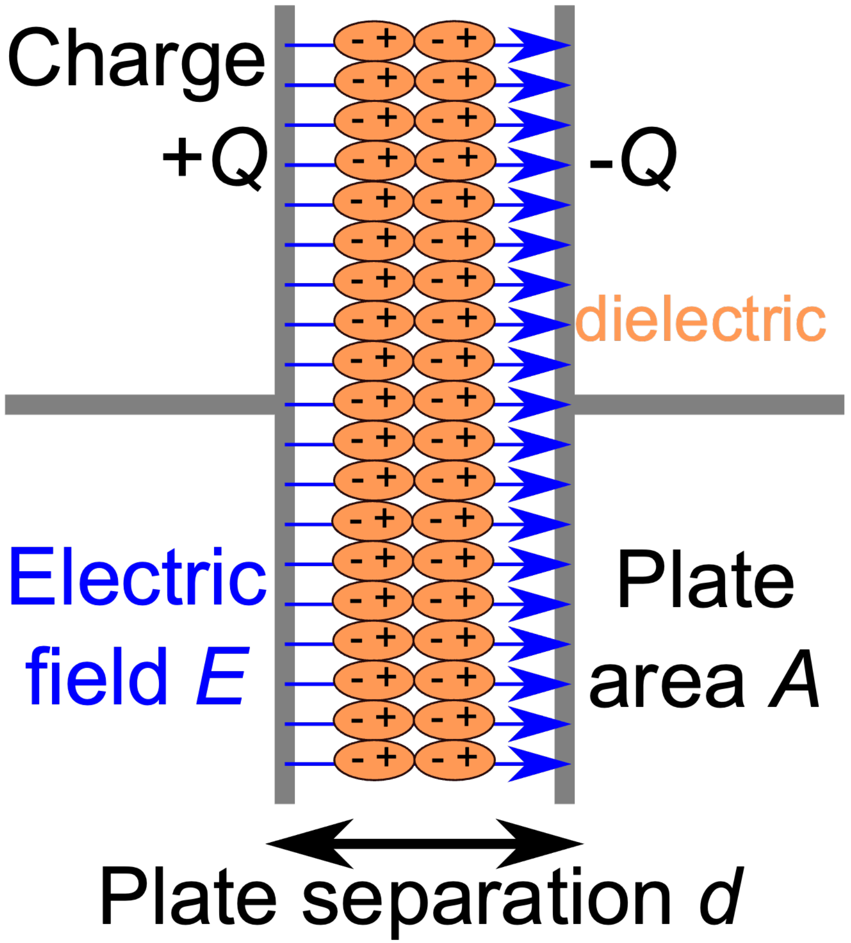


Giovanna 27, CC BY 4.0

[1] Physical Review B **59**, 93–96 (1999); [2] Applied Physics Letters **87**, 013115 (2005); [3] Applied Physics Letters **78**, 501–503 (2001); [4] Science Advances 6, eaax1085 (2020).

What is required for a capacitor?

commons.wikimedia.org/wiki/File:Capacitor_schematic.svg, CC BY-SA 3.0



- Two plates
- Electron number is coupled (Coulomb interaction)

$$\int dr\, dr' \rho_l(r) V(r - r') \rho_l(r')$$

- Fundamental capacitor equation:

Capacitance

$$dQ = C\, dV$$

Charge (electron density) — Voltage (potential difference)

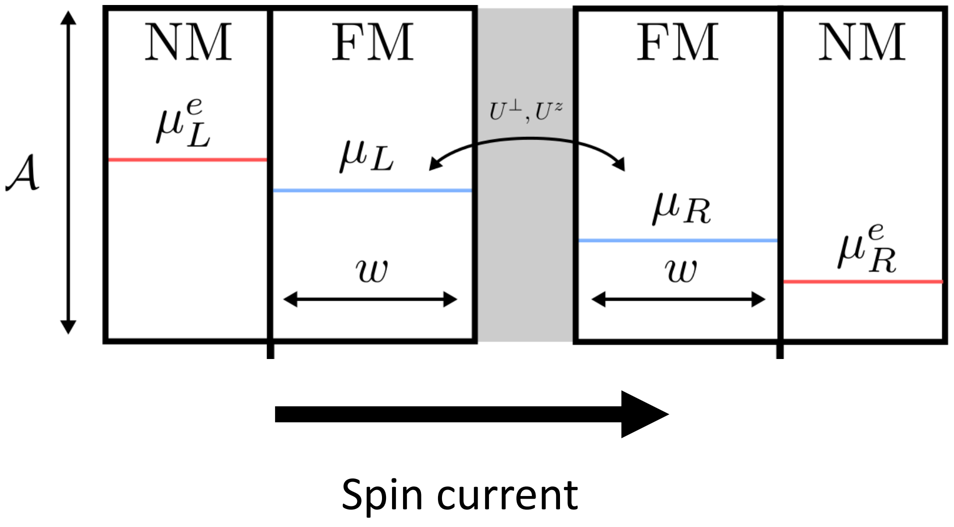
$$I = C \dot{V}$$

Magnon Spin Valve

- Two ferromagnets coupled by thin layer [1]
- Spin carried by magnons
- Coupling leads to spin current + density density interaction
- Coupling Hamiltonian

$$H_c = \sum_{ij} U_{ij}^{\perp}(S_L^x S_R^x + S_L^x S_R^x) + U_{ij}^z S_{L,i}^z S_{R,j}^z$$

Tunneling — Density-density interaction



[1] H. Wu *et al.* PRL **120**, 097205

Density-density interaction

- Coupling magnon number between two ferromagnets:

$$H^z = \sum_{ij} U_{ij}^z S_{L,i}^z S_{R,j}^z = -U_0^z \sum_{\boldsymbol{k}\boldsymbol{k}'} n_{\boldsymbol{k}}^L n_{\boldsymbol{k}'}^R$$

Magnon number

- If (relatively) weak, we can employ a mean-field approach:

Magnon chemical potential

$$n_{\boldsymbol{k}}^R = f_B\left(\frac{\hbar\omega_{\boldsymbol{k}} + U_{\boldsymbol{k}}^L - \mu_m^R}{k_B T}\right); \qquad U_{\boldsymbol{k}}^L = \mp U_0^z \sum_{\boldsymbol{k}'} n_{\boldsymbol{k}'}^L$$

Magnon number left

Magnon number right

Coupling of magnon charge to spin bias

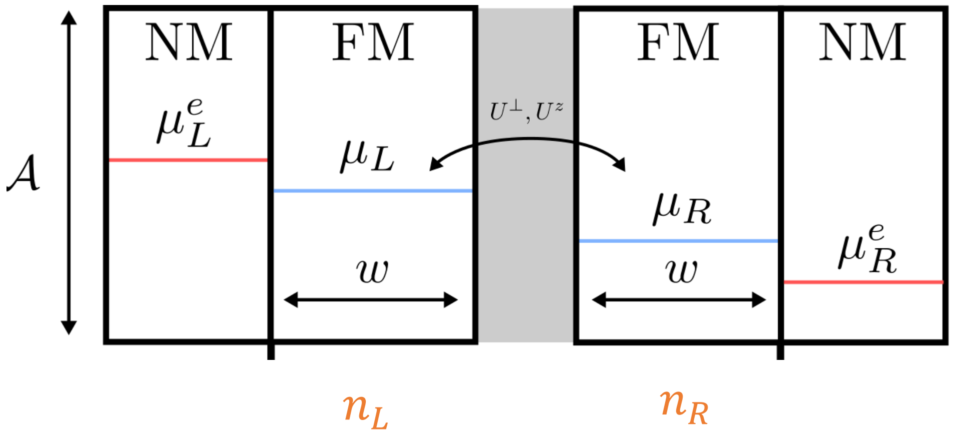
Define magnon charge $Q_m \equiv \hbar(n_L - n_R)$ and magnon voltage $V_m \equiv \mu_m^L - \mu_m^R$

Dynamics of magnon charge follow from mean-field approach $n_{\boldsymbol{k}}^R = f_B\left(\frac{\hbar\omega_{\boldsymbol{k}} + U_{\boldsymbol{k}}^L - \mu_m^R}{k_B T}\right)$;

$$n_L - n_R \sim \mu_m^L - \mu_m^R$$

$$\Downarrow$$

$$dQ_m = C_m\, dV_m$$



Magnon spin capacitor

$$dQ_m = C_m \, dV_m$$

Magnon charge is coupled to magnon voltage -> capacitor

Capacitance: $\frac{1}{C_m} = \frac{1}{C_M} + \frac{1}{C_Q}$

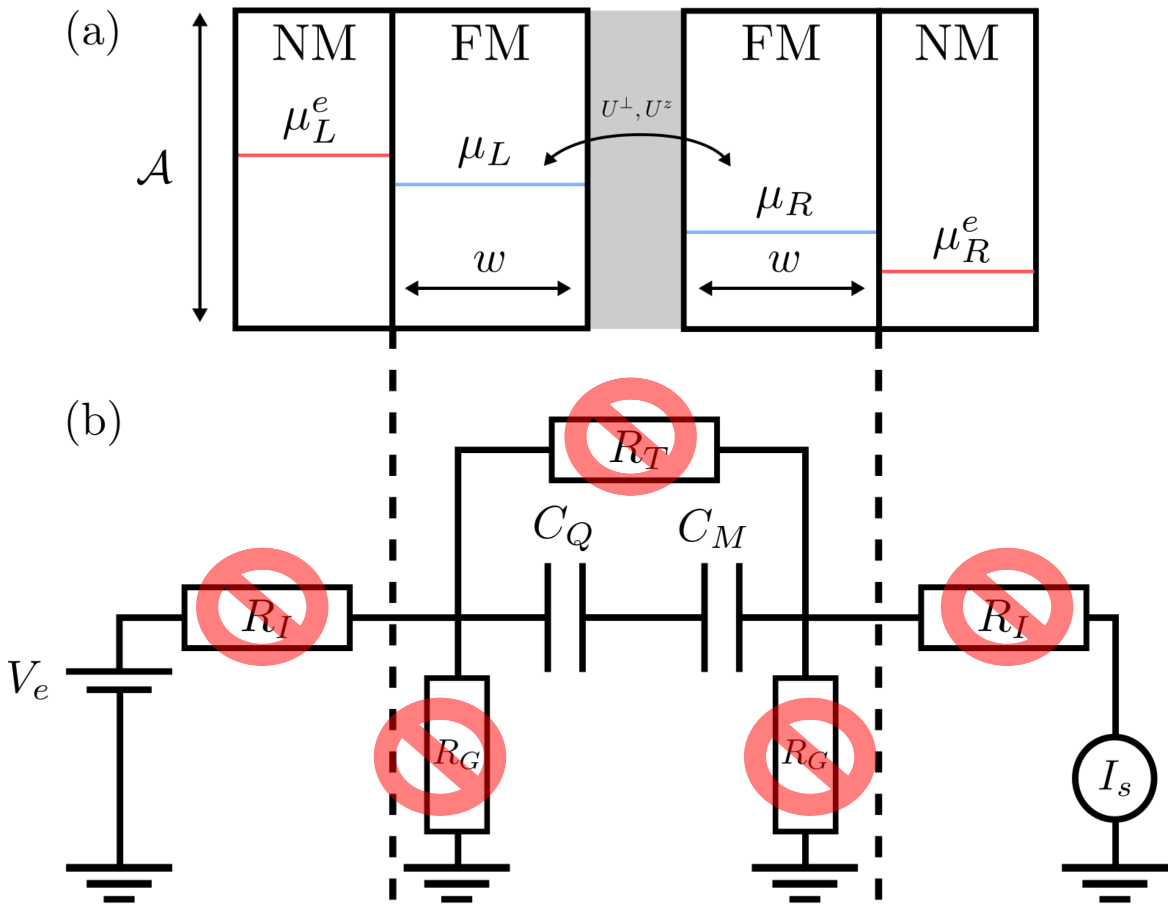
- C_M mutual capacitance -> result of density-density interaction
- C_Q quantum capacitance

Ferromagnetic junction

Resistances can be neglected in real world setups

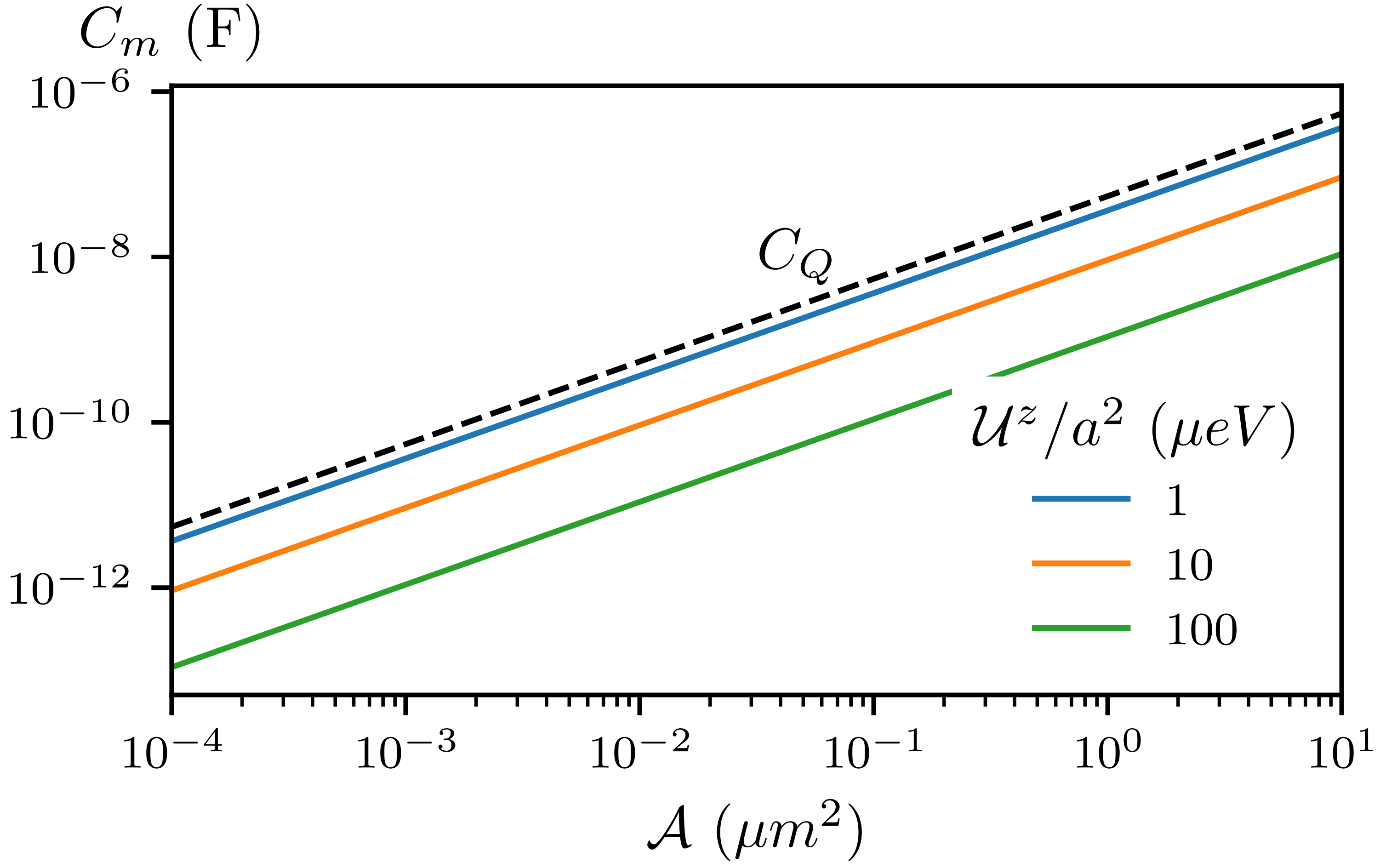
$$dQ_m = C_m\, dV_m$$

nanoseconds (*magnon-magnon scattering*) to microseconds (*decharging through Gilbert damping*)



Capacitance

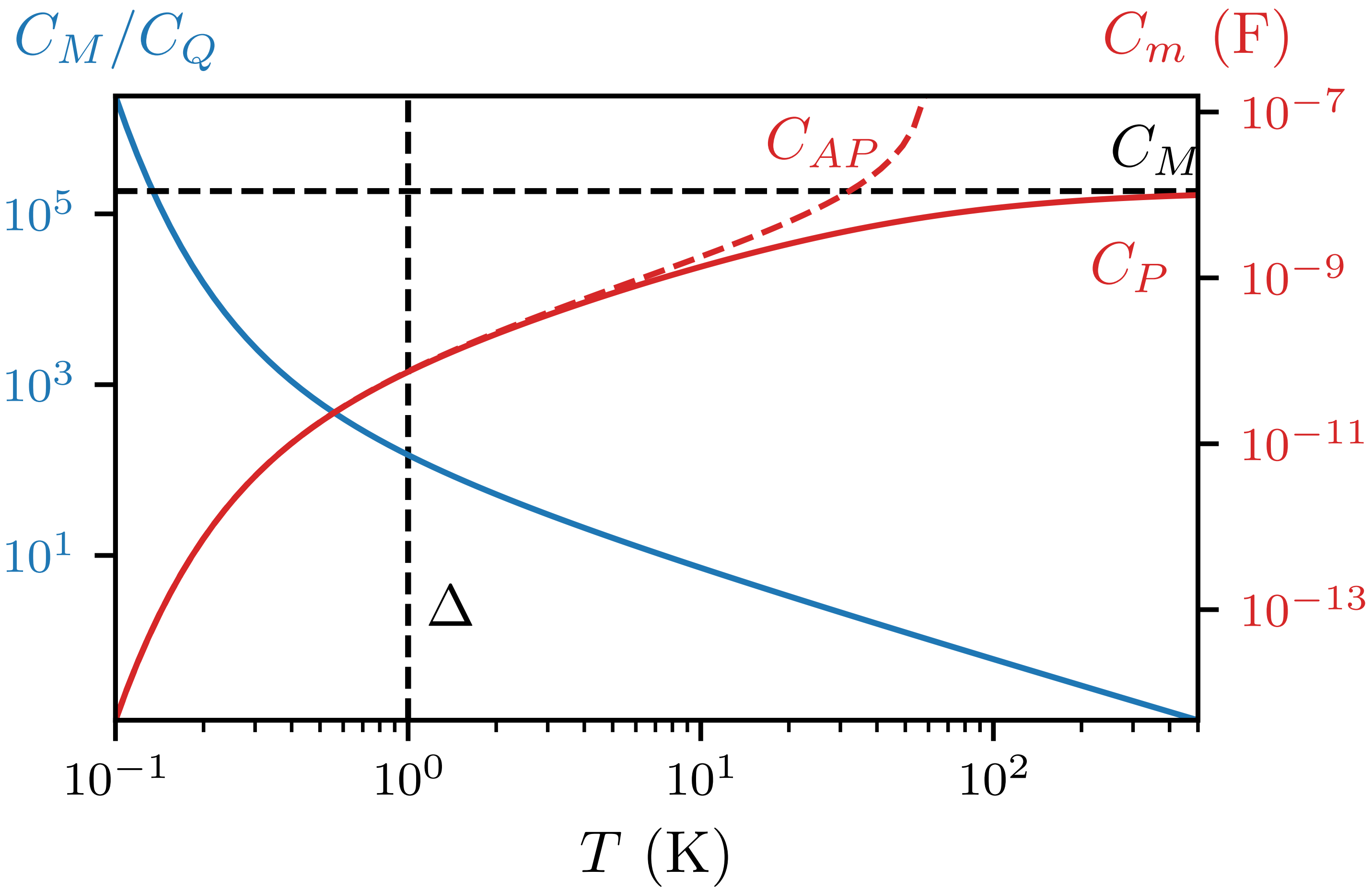
- Scales as area
- Interaction strength can be used to tune
- Limited by quantum capacitance:
- $\frac{1}{C} = \frac{1}{C_M} + \frac{1}{C_Q}$



Capacitance (antiparallel orientation)

- Parallel/antiparallel:
- $\frac{1}{C} = \frac{1}{C_M} \pm \frac{1}{C_Q}$

- Divergence of total capacitance: (dynamic) Stoner-like instability [1,2]



[1] Physical Review A 95, 053607 (2017).
[2] Physical Review Letters 113, 185302 (2014).

Conclusion

- Magnon spin valve behaves as spin capacitor
- To measure this: create an RC circuit:
  - DC response $I(t) \sim e^{-t/\tau}$
  - AC response: low-pass filter

Pieter M. Gunnink, Tim Ludwig, Rembert A. Duine, "*Magnon spin capacitor*", Appl. Phys. Lett. 124, 182404 (2024)