Lecture #6 : RF Inductors

RF Circuits = Analog Circuits + Inductors

Std. IC process does not include inductors.

Digital ICs → NMOS, PMOS, MOS capacitors + resistors (rarely)

Analog ICs → (above) + capacitors (MOM or MIM)

RF → (above) + inductors

passive inductors are indispensable! — LNAs, Mixers (Tx), VCOs, PAs

active inductors = higher noise, higher distortion, higher power

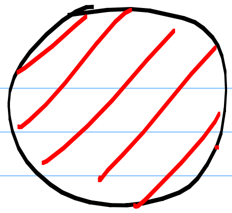
Take a step back — Skin Effect

DC – entire conductor cross-section is used for current flow.

AC – Faraday's Law : AC current flow establishes a magnetic field that induces an electric field whose associated currents (eddy currents) oppose the original current

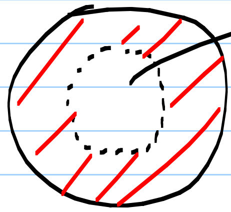
* This effect is strongest at the center of the conductor $(r=0)$ ⇒ current tends to flow in the outer portion of the conductor. Hence the name Skin Effect

DC:



$$R_{DC} = \frac{\rho l}{A} \text{ or } \frac{l}{\sigma A}$$

AC:



very little current

$$\frac{R_{AC}}{R_{DC}} \approx \frac{r}{2\delta}$$

where r = radius of cylindrical conductor

Skin depth $\boxed{\delta = \sqrt{\frac{2}{\omega \mu \sigma}}}$ $\equiv$ depth at which amplitude of fields decay by $\frac{1}{e}$

ω = angular frequency of operation (rad/s)

μ = absolute permeability of conductor (usually $= \mu_0$)

Skin depths in some materials at 2 GHz

$$\delta = \sqrt{\frac{2}{\omega \mu \sigma}} = \sqrt{\frac{2}{2\pi \cdot f \cdot \mu_0}} \cdot \sqrt{\frac{1}{\sigma}}$$

$$= \sqrt{\frac{1}{\pi \cdot (2 \times 10^9) \cdot (4\pi \times 10^{-7})}} \cdot \sqrt{\frac{1}{\sigma}}$$

$$= 1.126 \times 10^{-2} \sqrt{\frac{1}{\sigma}}$$

Al : $\delta = 1.126 \times 10^{-2} \sqrt{\frac{1}{3.816 \times 10^7}} = 1.82\,\mu m$

Cu : $\delta = 1.126 \times 10^{-2} \sqrt{\frac{1}{5.813 \times 10^7}} = 1.48\,\mu m$

Au : $\delta = 1.126 \times 10^{-2} \sqrt{\frac{1}{4.098 \times 10^7}} = 1.76\,\mu m$

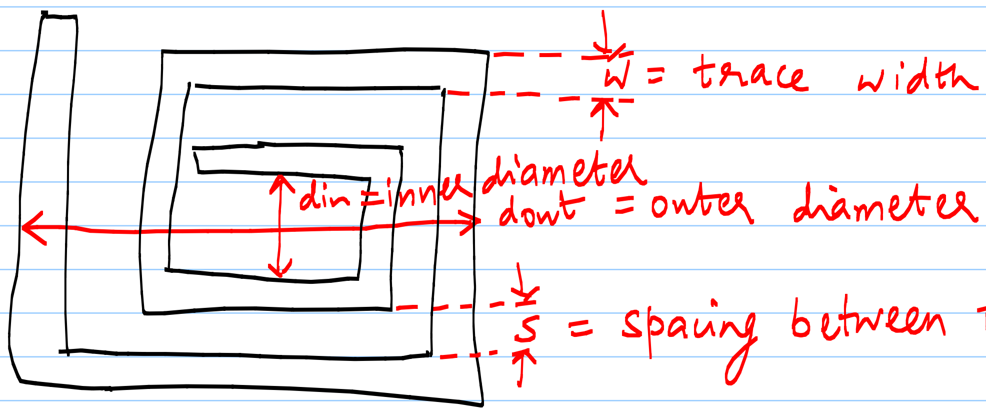
What are the IC options available for passive inductors?

* Bondwires
  - ~25 μm diameter, low resistivity
  - high Q (>20 in 1–10 GHz range)
  - Thumb rule ~ 1nH/mm length
  - Large variation in L value (15–20%) due to manufacturing tolerances (these are meant for IO & VDD–GND, not inductances)

* Spiral Inductors
  - On-chip metal traces laid out in a spiral shape
  - metal is either Al or Al–Cu alloy, so higher series resistance ($\rho_{Al} \approx 50\,m\Omega/\square$, $\rho_{Cu} \approx 25\,m\Omega/\square$)
  - low Qs in std. CMOS processes (Q<10 in 1–10GHz range)

* Only inductances <10nH are practical for IC implementation

* Origin of inductance: time varying magnetic flux produced by current-carrying strips of metal



* Degrees of freedom: W, S, din, dout (total area), n (number of turns)

* Intuitive dependence on geometry:

$L \propto$ core area

$L \propto n$

* $L_{tot.} = L + M$

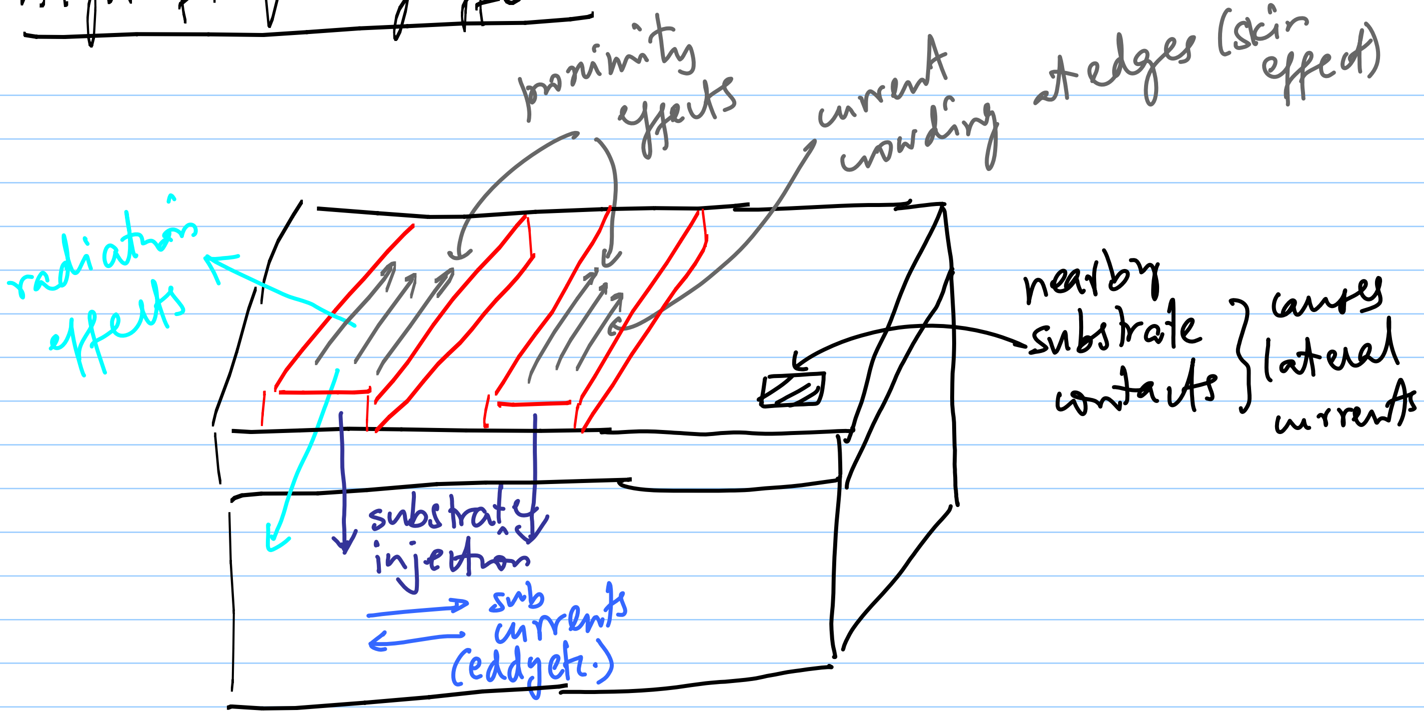
Self inductance — Mutual inductance

* Current in same direction ⇒ positive M
  - current in adjacent turns
* Current in opposite direction ⇒ negative M
  - currents in opposite sections of spiral
  - larger inner diameter ⇒ larger Q

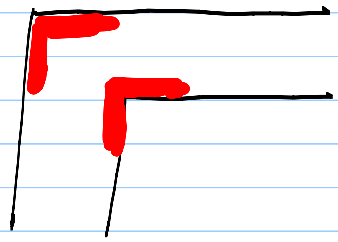
but also larger area!

⇒ leads to more "hollow" inductors.

High-frequency effects



1) Edge Effects : Avoid 90° routings for signal lines as much as possible



Crowding of charge carriers around edges due to sudden 90° change in current direction

$\boxed{\text{45° edges is allowed}}$

- larger current density
- larger resistance

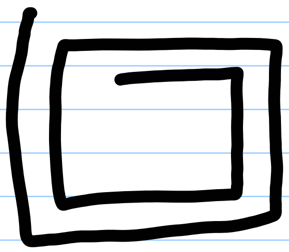
} lower Q

2) Substrate Losses :

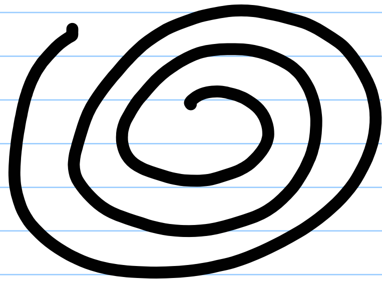
* Eddy currents are induced in semiconductor substrate $\Rightarrow$ magnetic losses to substrate
* Substrate losses $\propto$ area of inductor

Common Geometries:

Square spiral:

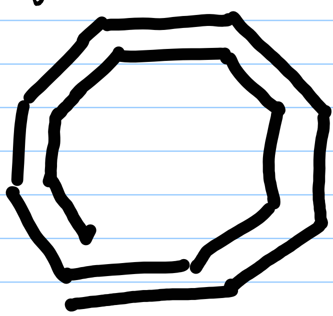


Circular Spiral:



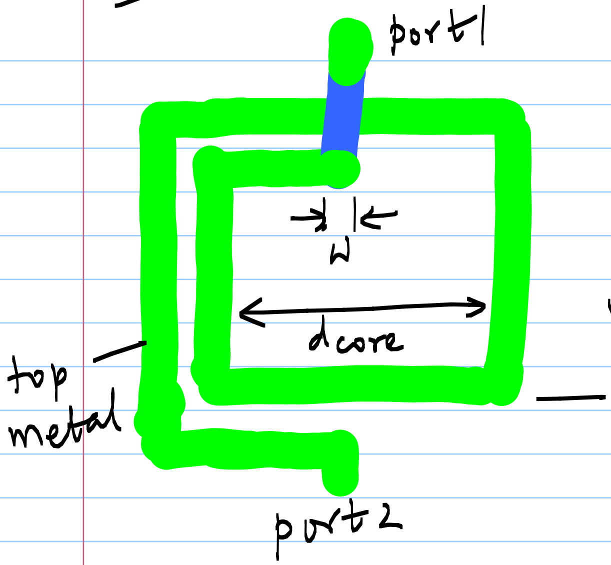
often not supported by process

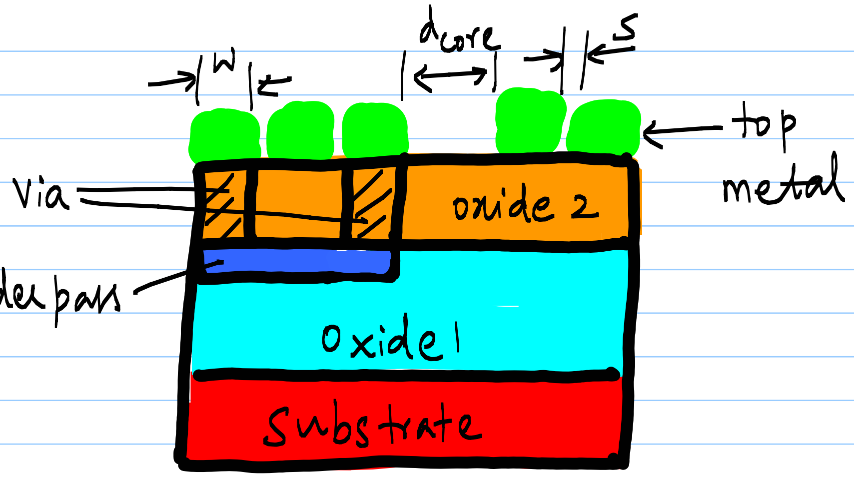
Octagonal Spiral:



* Circular spiral gives best Q
  - largest amount of metal in least area
  - No edge effects

e.g. Square Spiral on top metal, 1.5 turns





Layout – Top View   Vertical Cross-section

Note that the above inductor is asymmetric

* Need underpass to access both ports of inductor
* Q is often limited by underpass and via resistance

Spiral inductor modelling :

What do we need for a physical model?

1) Spiral inductance – $L_s \propto$ area, n
2) Series resistance – R_s

   obvious dependence : ρ of metal, thickness

   $R_s \propto$ length of conductor

   $\propto \dfrac{1}{\text{cross-sectional area}}$ $\left(\text{i.e. } \propto \dfrac{1}{\text{width}}\right)$

   other factors : skin, edge & proximity effects

3) Input-output coupling capacitance - C_c

- metal layer to underpass overlap
- coupling capacitance between turns

$C_c \propto$ area, metal-metal oxide thickness

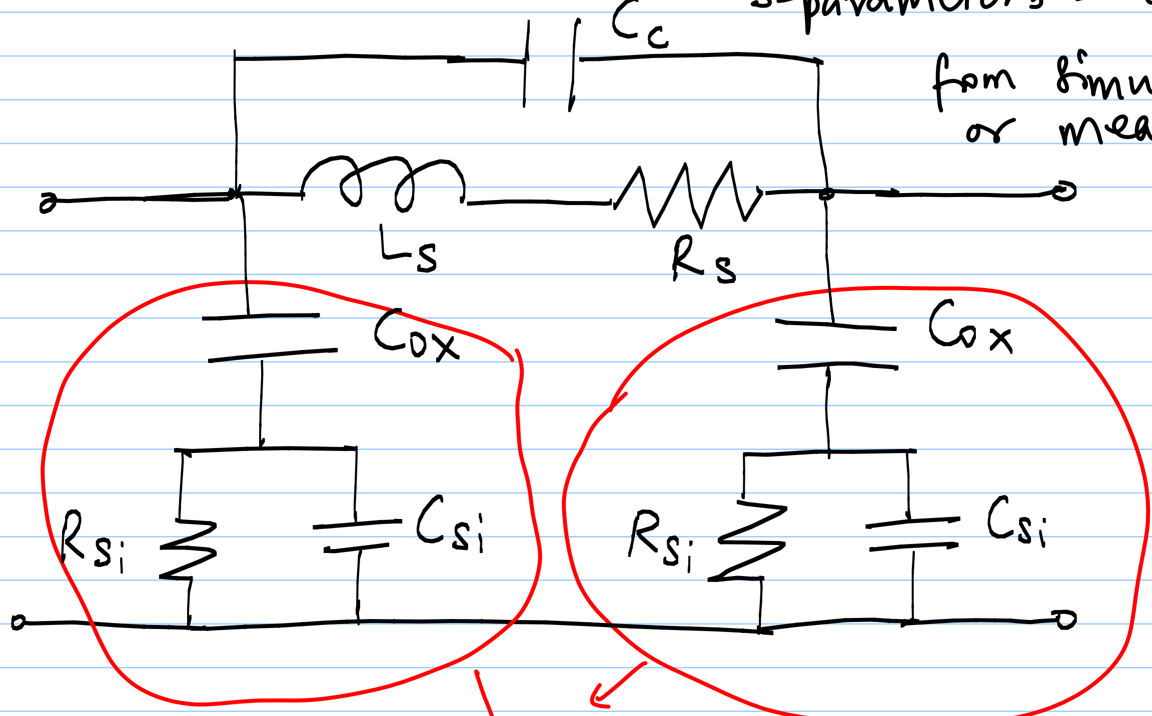
4) Capacitive coupling between spiral and lossy substrate through oxide - C_{ox}

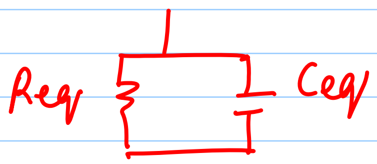
$C_{ox} \propto$ area, Spiral-substrate oxide thickness

5) Equivalent resistance and capacitance of substrate to ground - R_{si}, C_{si}

→ depend on doping levels etc. (substrate resistivity)

Lumped π-model (Usually extracted from S-parameters - obtained from simulation or measurement)





Sometimes simplified to R_{eq}, C_{eq} on each side

* Compact, simple & quite physical in nature
* Usually chosen to be symmetric (esp. if the inductor is symmetric)
* accurate over the frequency range of interest; for a good broadband fit, R_s may need to be a function of frequency (due to skin effect etc.)