Electromagnetic Properties Sensors

1. **Background** (DC to low frequency)
   - Materials have electromagnetic properties:
     - $\varepsilon_r$ → relative permittivity
     - $\mu_r$ → relative permeability
     - $\sigma$ → electrical conductivity
   - Electrical circuits can be built that interact with "nearby materials" that affect circuit performance
     - $\varepsilon_r$ → $C$
     - $\mu_r$ → $L$
     - $\sigma$ → $R$
   - Can be used to detect the presence of or even the identity of an object

a. **Electrical Conductivity Sensing**
   - 2 bare electrodes
   - Resistance is measured between them
   - Can range from open to a short

b. **Capacitive Sensing**
   - Parallel Plate Electrodes
     - $C_0 = \frac{\varepsilon_0 A}{d}$
     - $C_t = \frac{\varepsilon_0 \varepsilon_r A}{d}$
     - $\frac{C_t}{C_0} \approx \varepsilon_r$ of object
2. Fringing Field Electrodes
   - May use IDT structure

\[ A_{eq} \gg d^2 \]

Most of the capacitance is due to the fringing fields outside of the plane of the electrodes.

- Materials with \( \varepsilon > 1 \) interacting with the fringing fields will increase the measurable capacitance.

3. Inductive Coils
   - Or planar coil
   - Non-planar coil

- Materials with \( \mu \neq 1 \) interacting with the magnetic fields around the traces of the coils will affect the measurable inductance.
2. Implementation
   a. Traditional MEMS
      - bare electrodes, IDT structures, even coils can be made on a MEMS chip

   1) [Diagram of passivation, SiO2 die, backside solder balls, TSVs, metal trace opening in the passivation exposing the bare electrode ends]

   2) Capacitive Sensor
      - thin passivation (over IDTs)

   3) Inductive Sensor
      - thin metal coil, SiO2 die, thin passivation over coil
b. Printed Circuit Board Technology

1. PCB structure

- 2-layer PCB
- FR-4 (E-Glass)
- solder mask (polymeric layer)
- patterned Cu cladding

PCBs → less expensive than MEMS
→ much shorter development cycle
→ easy to attach electronics
→ can be much larger than Si die
→ cannot have nearly as small features as MEMS (Si-MEMS)

→ show examples + test data

2. Flexible PCBs, too

- polyimide
- LCP
PCB EC Sensor to Measure Saltwater Intrusion

Sensor Resistance Measurement for Various Water Samples

Resistance, \( \Omega \)

- Sea Water
- Turkey Creek
- Lake Jackson

Turkey Creek

Resistances (Ohms)

Percentage Salt Water
PCB Fringing Field Sensor to Measure Mass of Water Drop

Capacitance vs. Mass

R² = 0.9982
PCB Fringing Field Sensor to Measure Moisture Content of Soil

Measured Capacitance vs. Water Content of Soil

Estimated Dielectric Constant vs. Water Content of Soil