Effect of film thickness and electrode material on space charge formation and conductivity in polyimide films

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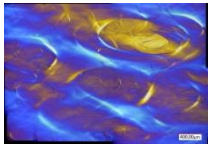
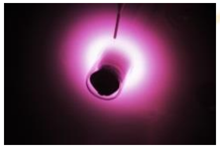
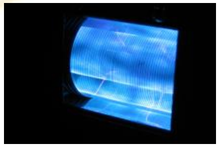
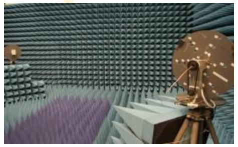
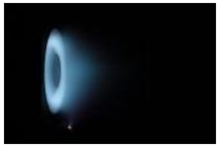





Presentation overview

Polyimide (PI)

- **Dielectric** polymer with:

Electrical properties:
- E_{BR} > 2 MV/cm (high)
- Tan(δ) < 10^{-2} (low)
- $\varepsilon_r \approx 3$

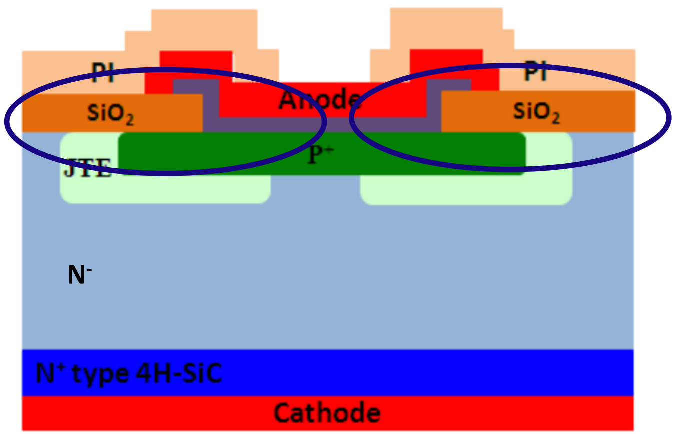
Thermal stability:
- Weight losses <1% at 500 °C (low)
- $T_{max} \approx 350$°C

Mechanical properties:
- Good adherence
- Low thermal expansion

➡ PI used as **passivation layer in power devices**

➡ Protection:
  - Electrical
  - Chemical
  - Mechanical

⚠ Important field reinforcement



4H-SiC PiN diode

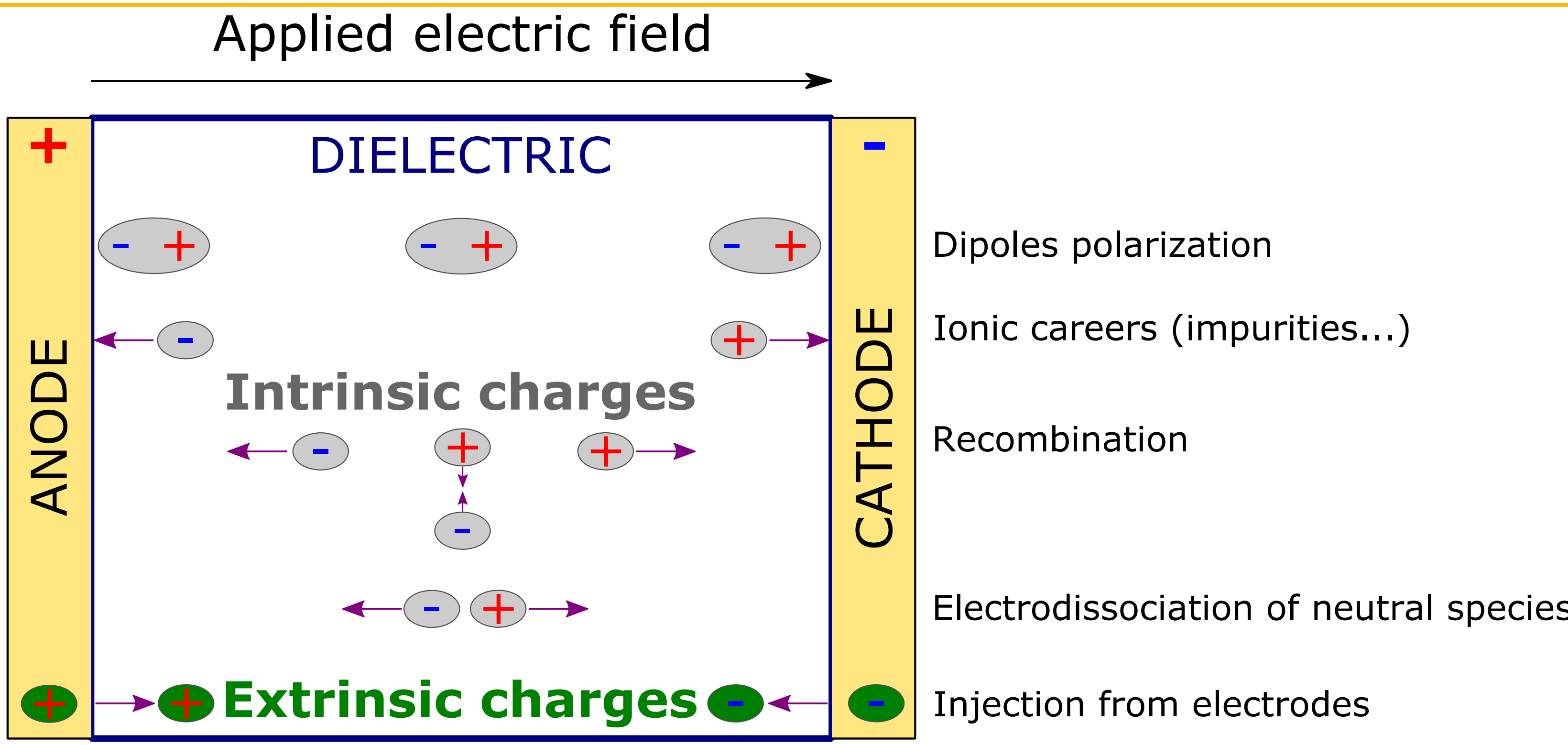
➡ **PI-thickness < 30 µm**

➡ **Emergence of wide band gap semiconductors** (such as SiC)

⬆ **Increasing constraints:**
  - **Electrical (high voltage)**
  - Thermal (high temperatures)

➡ **Importance** to **characterize** the **space charge behavior at high voltage**

What is space charge ?



- Space charge: All charges contained in a dielectric layer
- Cause of a **premature breakdown** of the material
- The space charge **changes the distribution of the internal electric field** → $\frac{dE}{dz} = \frac{\rho(z)}{\varepsilon}$

→ Importance of the space charge behavior knowledge

Purpose of the study

Objectives:

- Characterize the space charge behavior of **thin** PI samples (**< 20 µm**)
- Determine the impact of a **high DC stress** (= application of a DC external electric field) on space charge behavior in these samples
- Determine if the **electrode metal** would present an influence on the PI electrical behavior
- Determine if the **PI-thickness** would present an influence on the PI electrical behavior

<u>State of the art:</u> Study of space charge done only on **thick** PI-layers (>**100 µm**)[1,2,3]

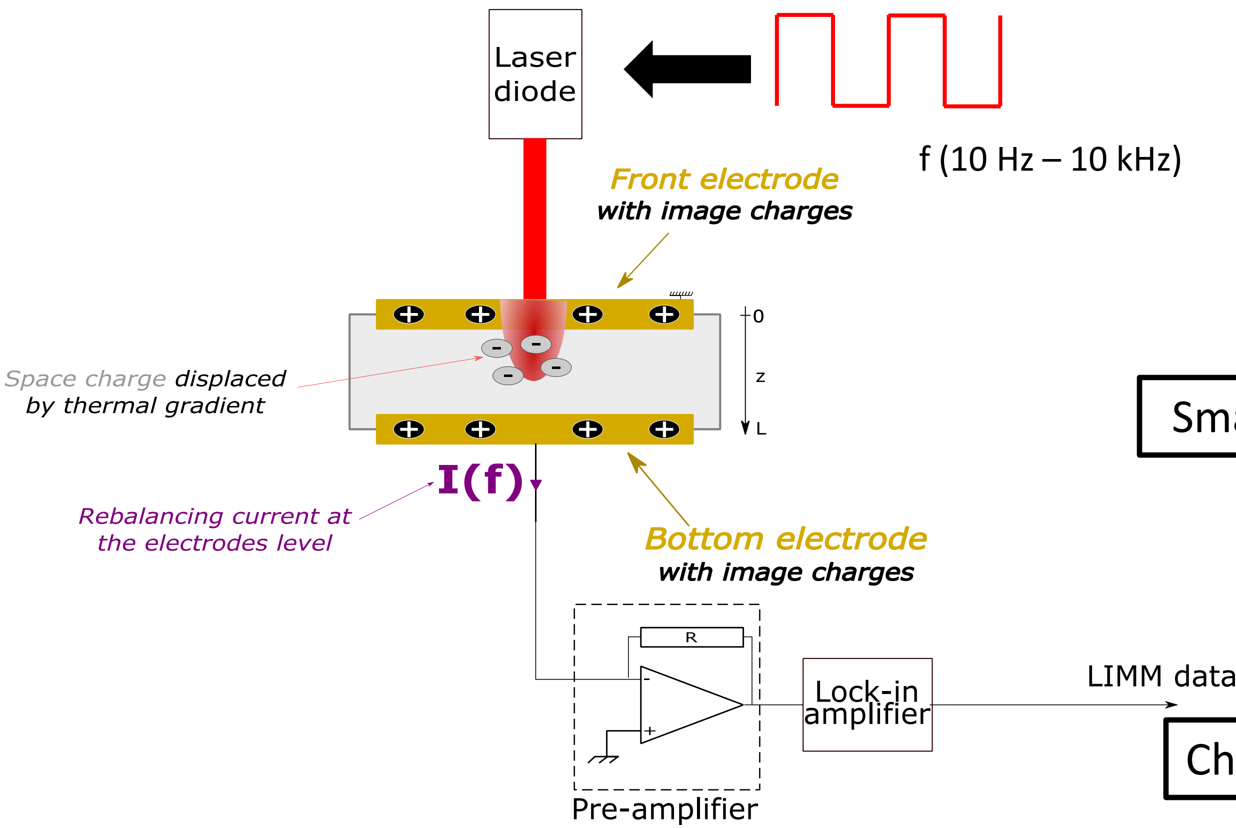
Experimental set-up used:

1. **L**aser **I**ntensity **M**odulation **M**ethod (LIMM) in order to characterize space charge dynamics in PI films → **Technique suitable with thin samples**
2. Complementary measurements with I(V) set-up to observe charge transport.

1 Y. Kishi, T. Hashimoto, H. Miyake, Y. Tanaka, et T. Takada, « Breakdown and space charge formation in polyimide film under DC high stress at various temperatures », Journal of Physics, 2009.
2 T. Takada, H. Miyake, Y. Tanaka, M. Yoshida, et Y. Hayase, « Quantum chemical calculation studies on hetero charge accumulation in polyimide film containing water », CEIDP, 2013.
3 S. Akram, J. Castellon, S. Agnel, et M. Khan, « Space Charge Analysis of Multi-Structure Polyimide Films using TSM », CEIDP, 2018.

LIMM: Laser Intensity Modulation Method (1/3)

Thermal method to carry out space charge measurements in thin dielectric layers
(5 µm < thickness < 100 µm)



Thermal gradient

↓

Local permittivity
Local thermal expansion

↓

Small displacement of space charge

↓

Electrostatic unbalancing

↓

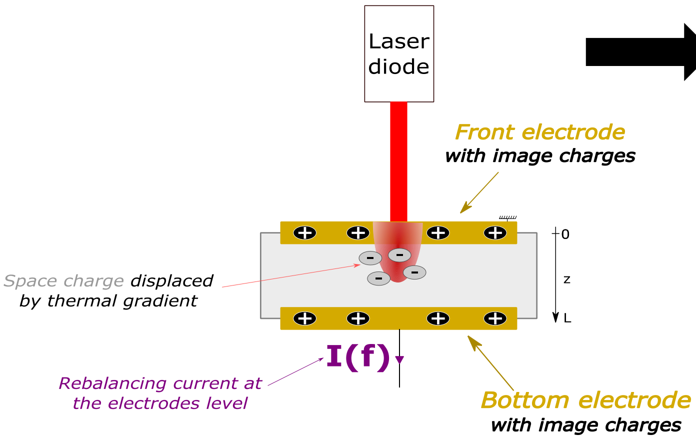
Change of image charges quantity

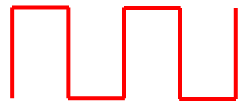
↓

Rebalancing current between electrodes

LIMM: Laser Intensity Modulation Method (2/3)

Thermal method to carry out space charge measurements in thin dielectric layers
(5 µm < thickness < 100 µm)



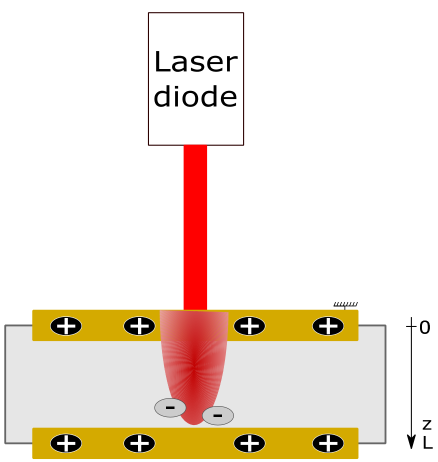


f (10 Hz – 10 kHz)

$$\delta_t = \sqrt{\frac{D_t}{\pi f}}$$

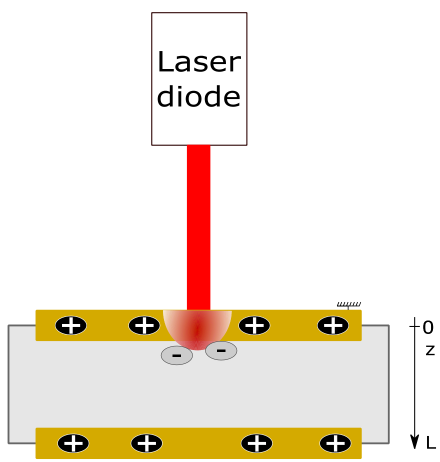
Penetration length of the thermal gradient

LOW FREQUENCY



f ≈ 10 Hz

HIGH FREQUENCY



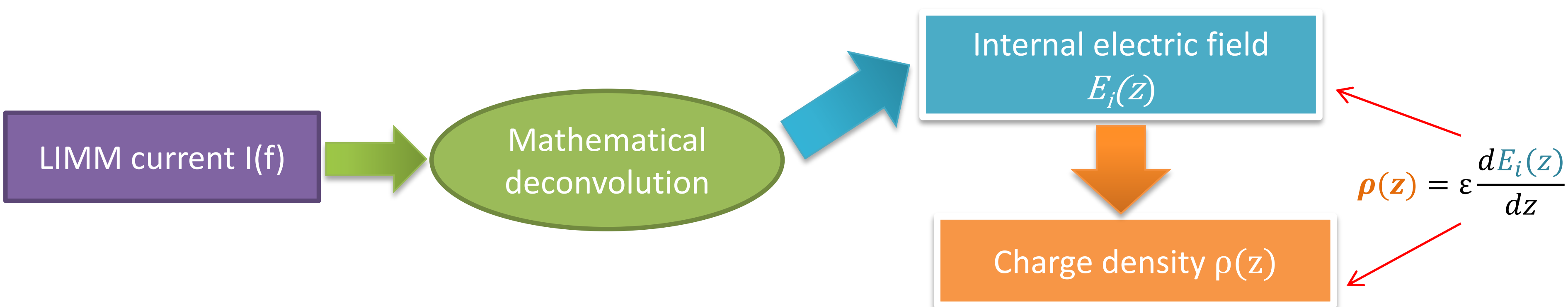
f ≈ 10 KHz

Frequency scan to have a charge profile along z

LIMM: Laser Intensity Modulation Method (3/3)

$$I(f) = j\omega \frac{S}{L} \int_{0}^{L} \left[p(z) - \varepsilon(\alpha_z - \alpha_\varepsilon) E_i(z) \right] T(z,f)\, dz$$

Measured *Polarization* *Internal electric field* *Simulated and calibrated*



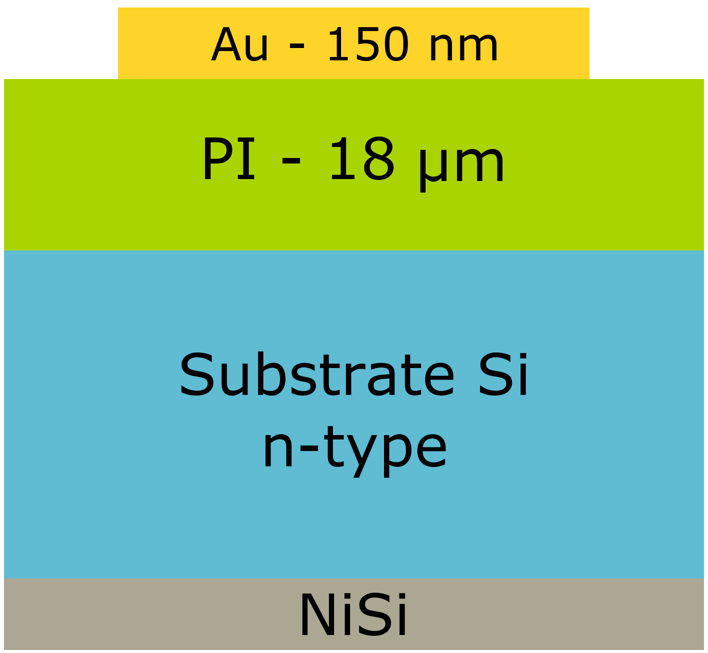
Samples

Wafer
Type: n^+ silicon
Diameter: 3 inches

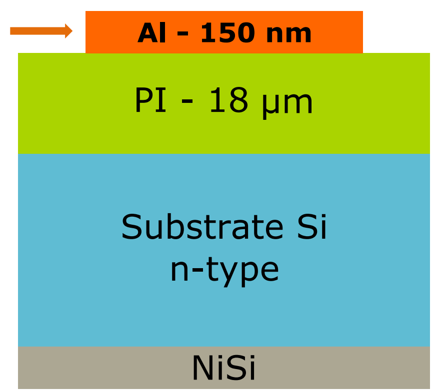
Top electrode
Type: Gold → Aluminium
Thickness: 150 nm
Diameter: 16 mm
Deposition: Sputtering

Polyimide
Thickness: 18 µm → 12 µm
Deposition: Spin-coating

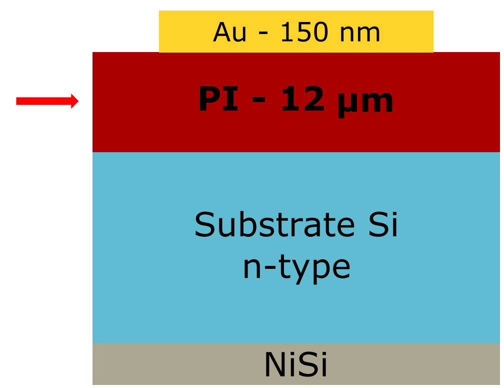
Reference



Electrode metal



PI-layer thickness

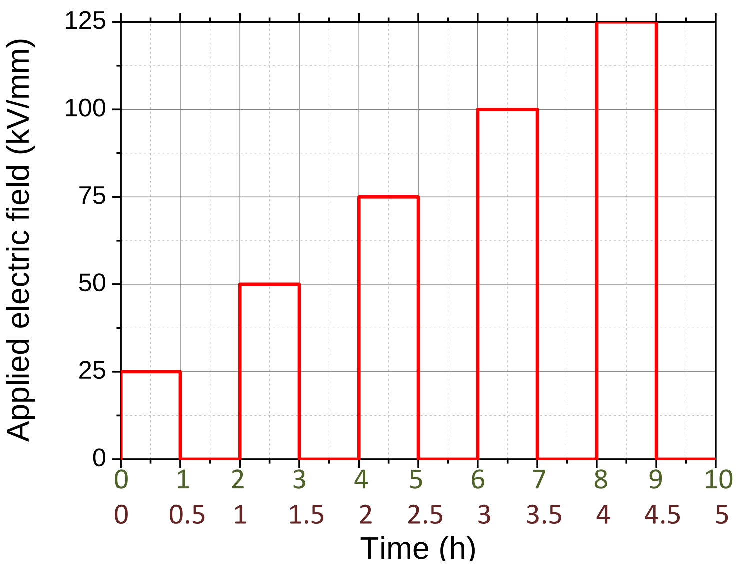


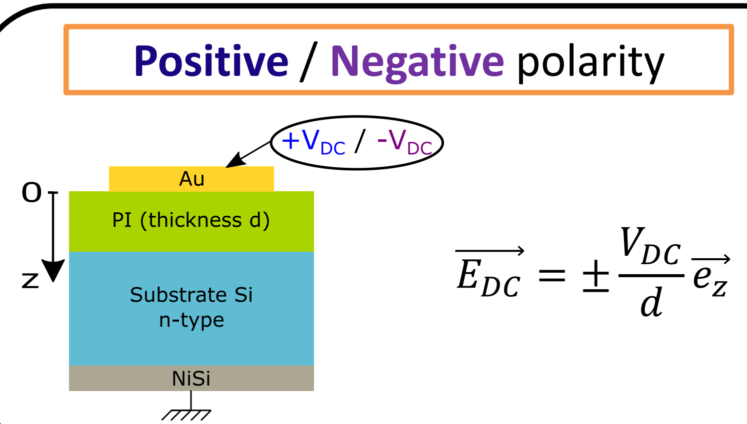
Experimental protocols (1/2)

Objective: Determine **charge and field profiles** / **conduction current density** after the application of increasing external electric fields applied cumulatively on a **virgin** and **dried** sample at room temperature.

Polarization steps:

- External electric constraints: 25 / 50 / 75 / 100 / 125 kV/mm
- Duration of each step: **60 min / 30 min**
- Polarity: **+** and **-**



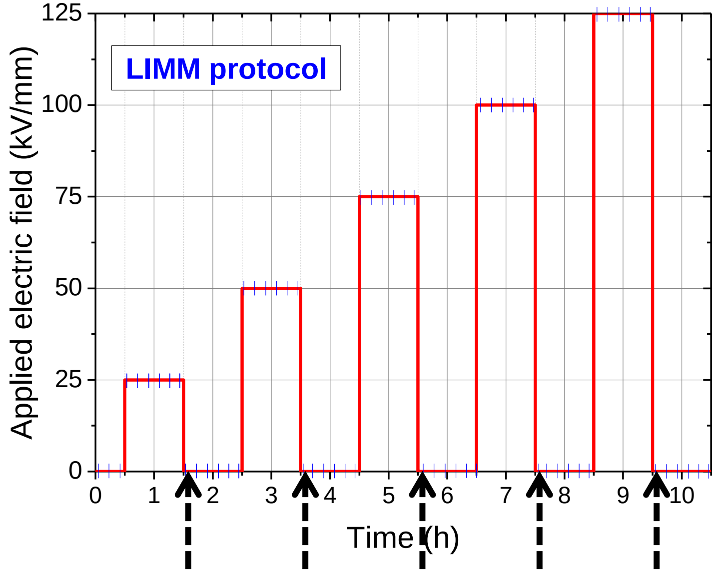


$$\overrightarrow{E_{DC}} = \pm \frac{V_{DC}}{d} \overrightarrow{e_z}$$

Definition of polarity

Experimental protocols (2/2)

LIMM protocol



Measurements that will be presented after

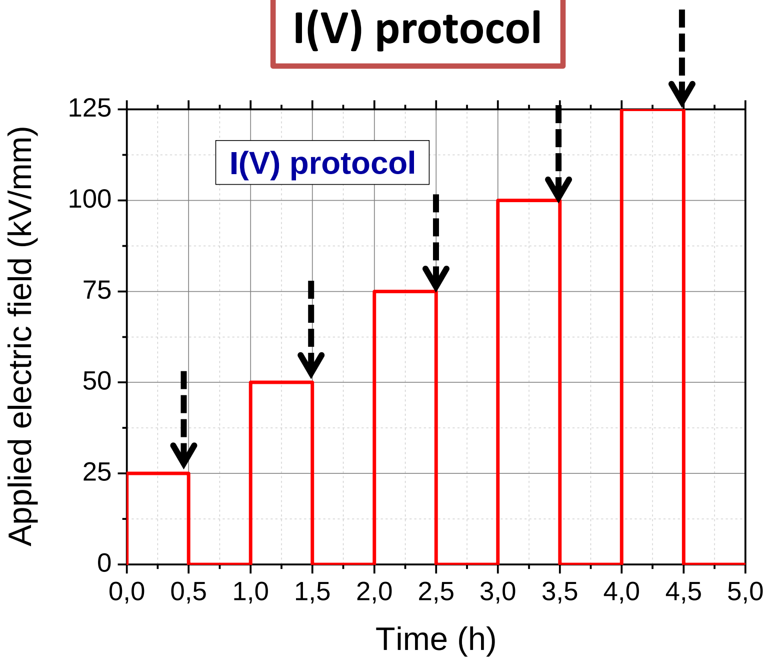
LIMM measurements characteristics:

- Frequency range: [10 Hz; 10 kHz]
- Number of frequencies: 63
- Duration: 10 min

Presented results:

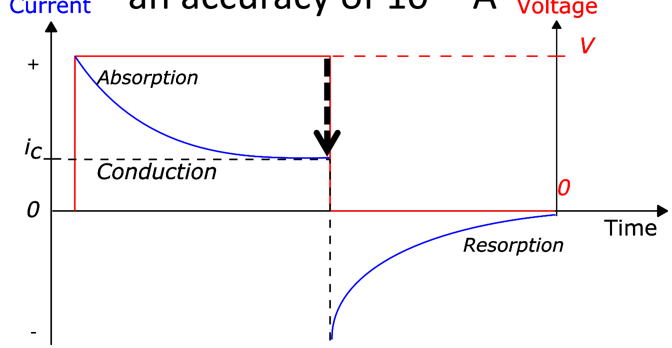
- **Internal electric field distribution**
- **Charge density profile**

I(V) protocol

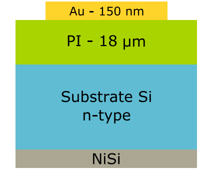


Transient currents are measured:

- Each second
- With a Keithley electrometer with an accuracy of 10^{-14} A

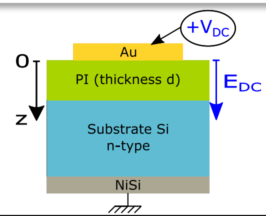


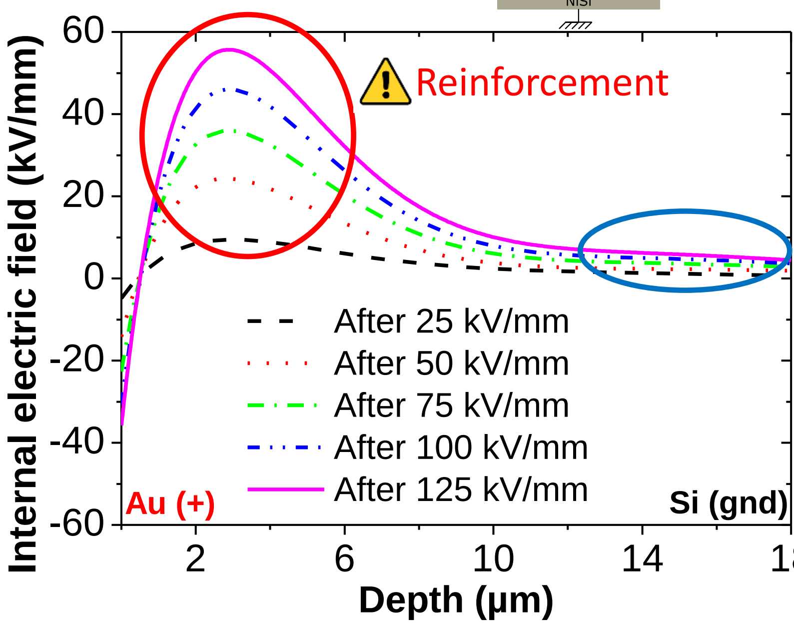
Influence of DC stress
Internal elecric field distribution



Positive polarity / $V_{DC} > 0$ / Au(+)

$$\overrightarrow{E_{DC}} = \frac{V_{DC}}{d}\overrightarrow{e_z}$$

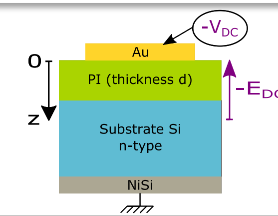


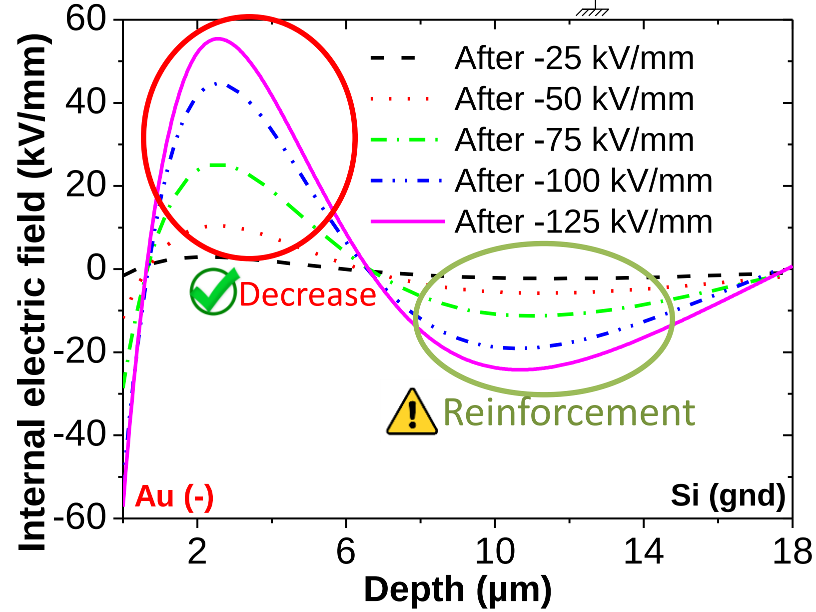


- Total field **reinforcement**
  => At 125 kV/mm total field of **180 kV/mm** !!
- Positive field with low values

Negative polarity / $-V_{DC} < 0$ / Au(-)

$$\overrightarrow{E_{DC}} = -\frac{V_{DC}}{d}\overrightarrow{e_z}$$

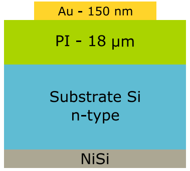




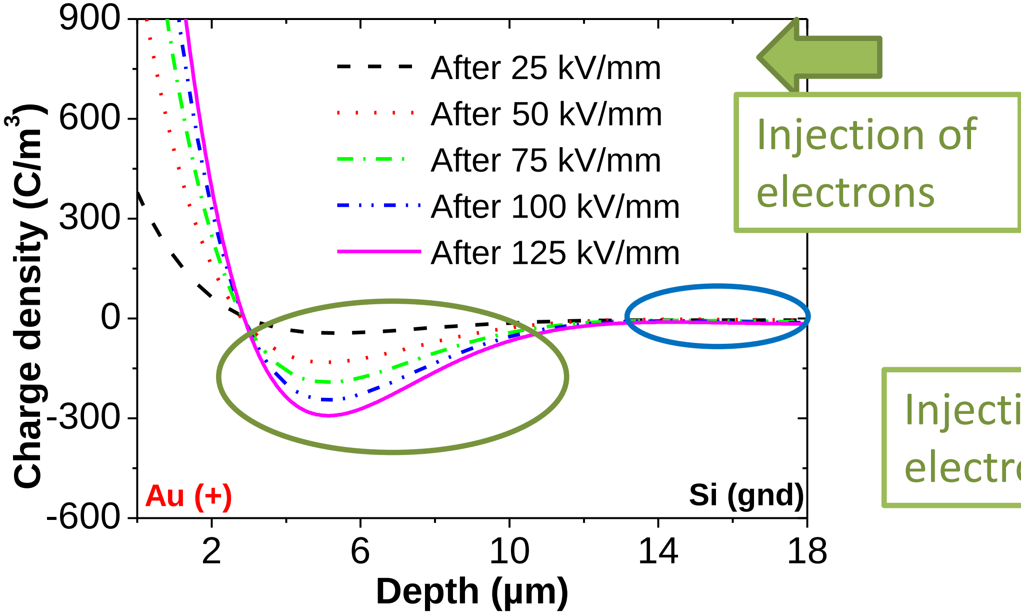
- Total field **decrease** (total field of **-70 kV/mm** at -125 kV/mm)
- Negative field. Total field **reinforcement**
  => At -125 kV/mm total field of **-150 kV/mm** !!

Influence of DC stress

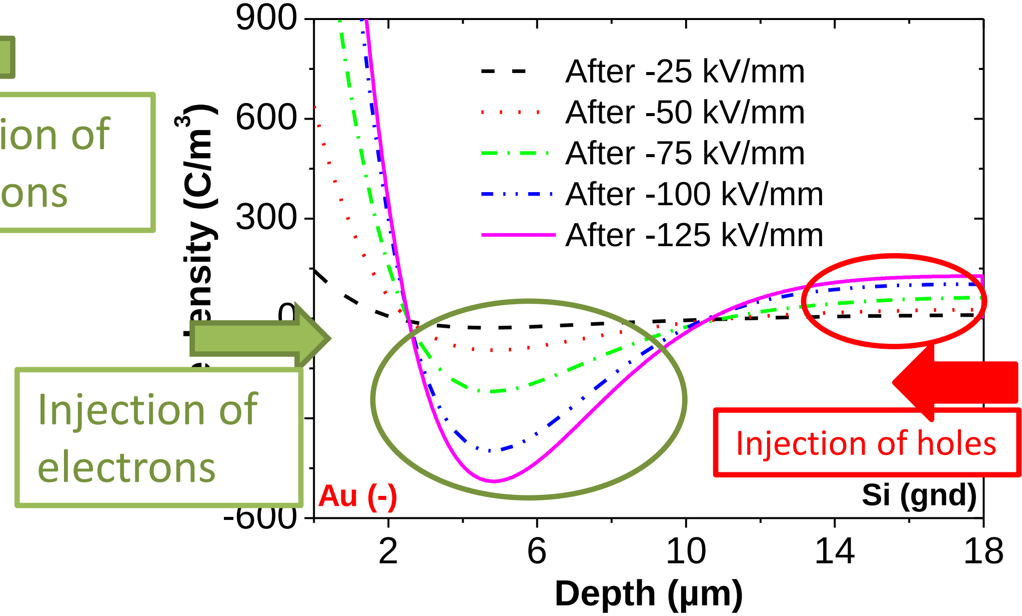
Charge density profile



Positive polarity / $V_{DC} > 0$ / Au(+)



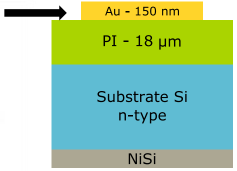
Negative polarity / $-V_{DC} < 0$ / Au(-)

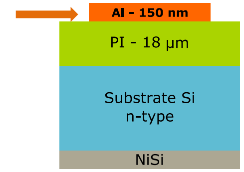


- Build-up of negative charges. Probably injected
- Mean charge density near zero (positive and negative charges compensate)

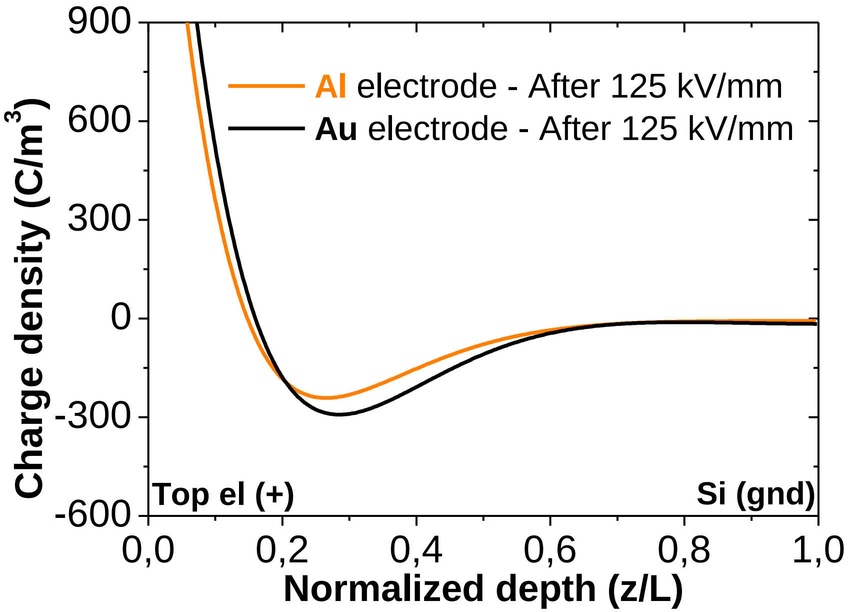
- Build-up of negative charges. Probably injected
- Build-up of positive charges. Probably injected from the substrate

Impact of electrode metal
Charge density profile



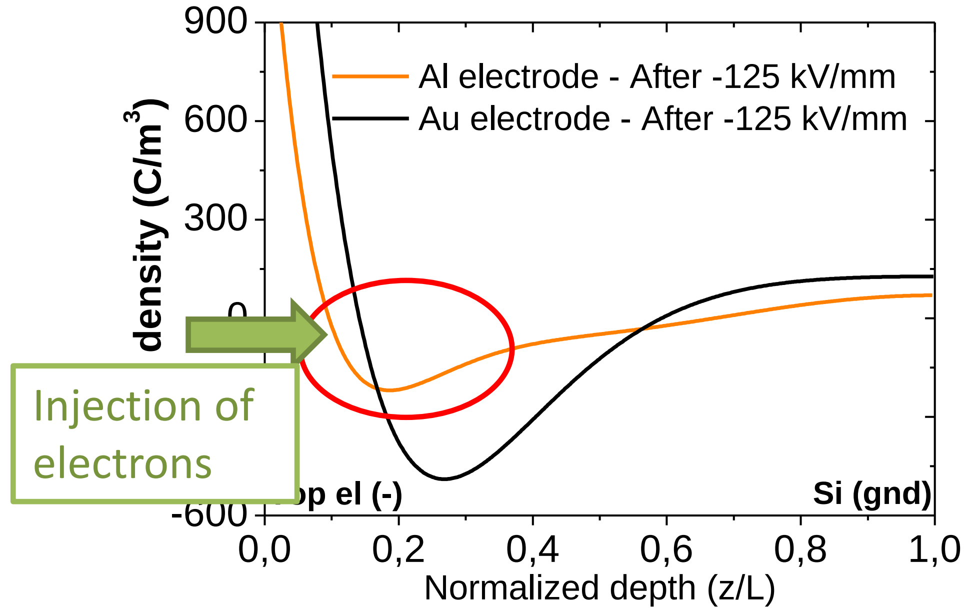


Positive polarity / $V_{DC} > 0$ / Au(+)

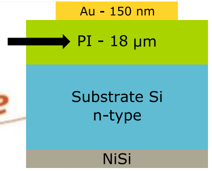


→ **Very similar profiles**

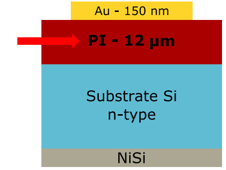
Negative polarity / $-V_{DC} < 0$ / Au(-)



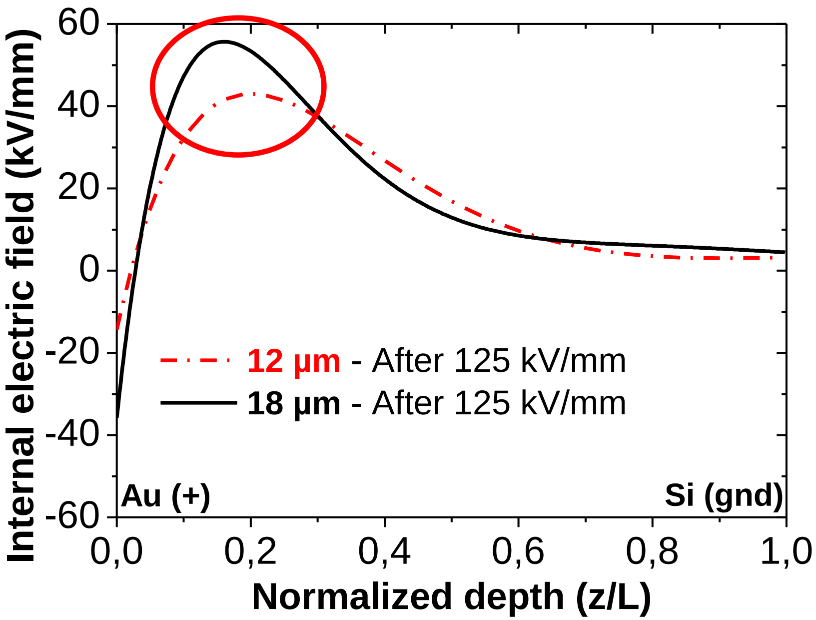
- **Decreased negative charge** density in the bulk of PI-layer with an **aluminium** electrode
- Can be due to **alumina** oxide formed between electrode and PI
- **Agreement** with the hypothesis of **electrons injected** from top electrode under a negative polarity



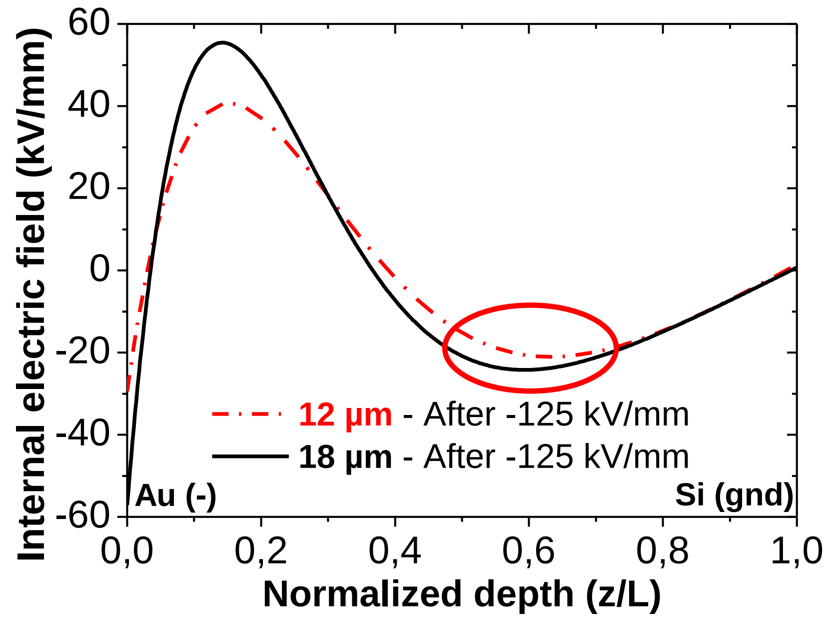
Impact of PI-thickness
Internal electric field distribution



Positive polarity / $V_{DC} > 0$ / Au(+)

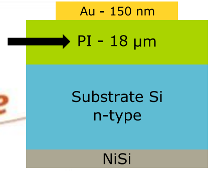


Negative polarity / $-V_{DC} < 0$ / Au(-)

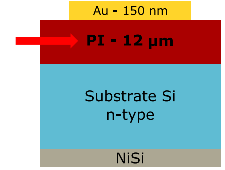


→ For both polarities, internal electric **field** is **decreased** when **PI-thickness** is **reduced**

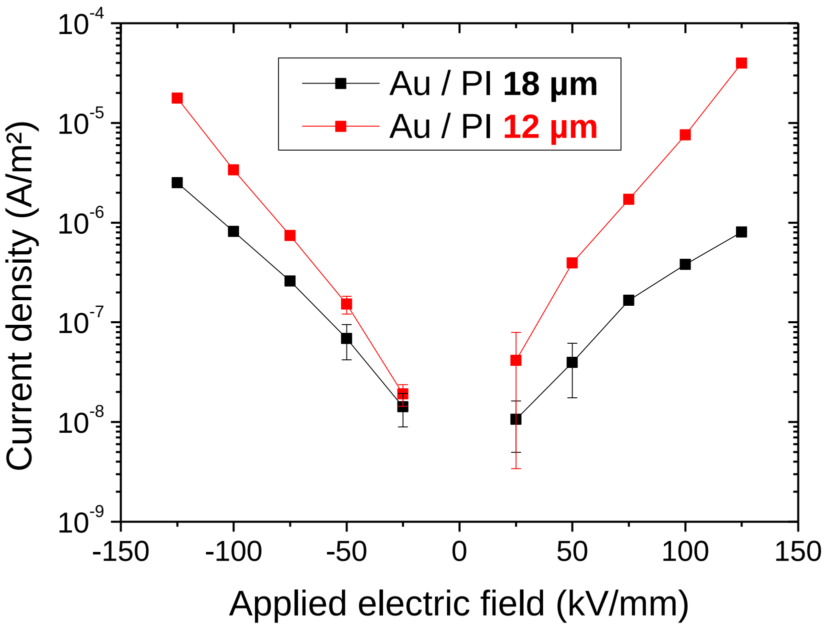
→ Diminution of the field reinforcement when the PI-thickness is lower



Influence of DC stress and PI-tickness *I(V) measurements*

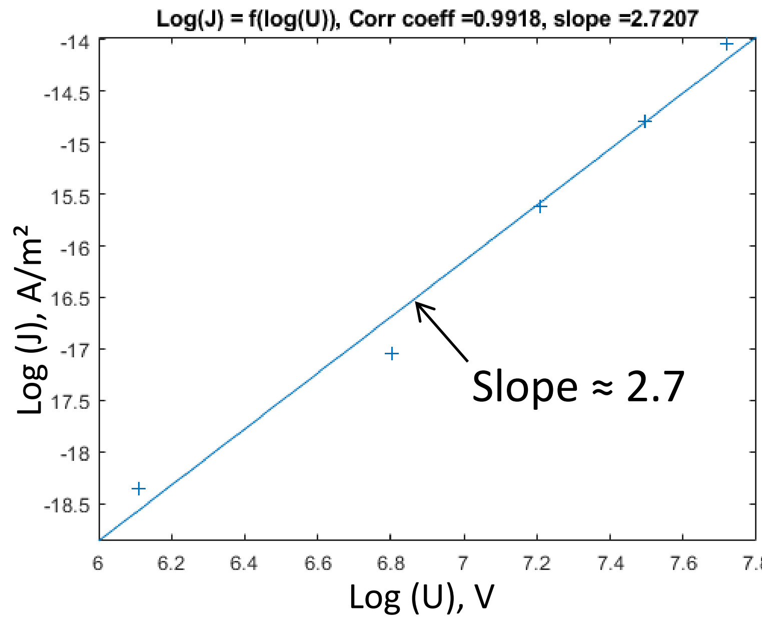


Conduction current density vs E_{ap}



- Current density increases with applied electric field for both polarities
- Symmetrical behavior with polarity
- Current density increases when PI-thickness decreases

Log log representation



Slope > 1

→ **Non-ohmic** region

→ **Injected carriers** are dominant

→ **Agreement with** the hypothesis of **injection from electrodes**

Conclusion

- LIMM is a suitable technique to determine charge profile and field distribution in thin polyimide films (<20 µm) under high DC electric fields in the range ±25 to ±125 kV/mm.
- An important field reinforcement is observed at high DC stress due to the presence of space charge under both polarities.
- A large increase in negative charges depending on a DC stress was observed under both polarities, which suggests that electron injection occurs under both polarities.
- The native alumina layer formed between the Al top electrode and the polyimide acts very likely as an electronic barrier when the polarity is negative. This behavior is in agreement with the hypothesis of injection.
- PI-thickness has an impact on the electrical behavior of PI. The field reinforcement increases when the PI-thickness is higher.

Thank you for your attention