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Optimal frequency range selection for full *C-V* characterization above 45MHz for ultra thin (1.2-nm) nitrided oxide MOSFETs

by

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Integrate Ideas

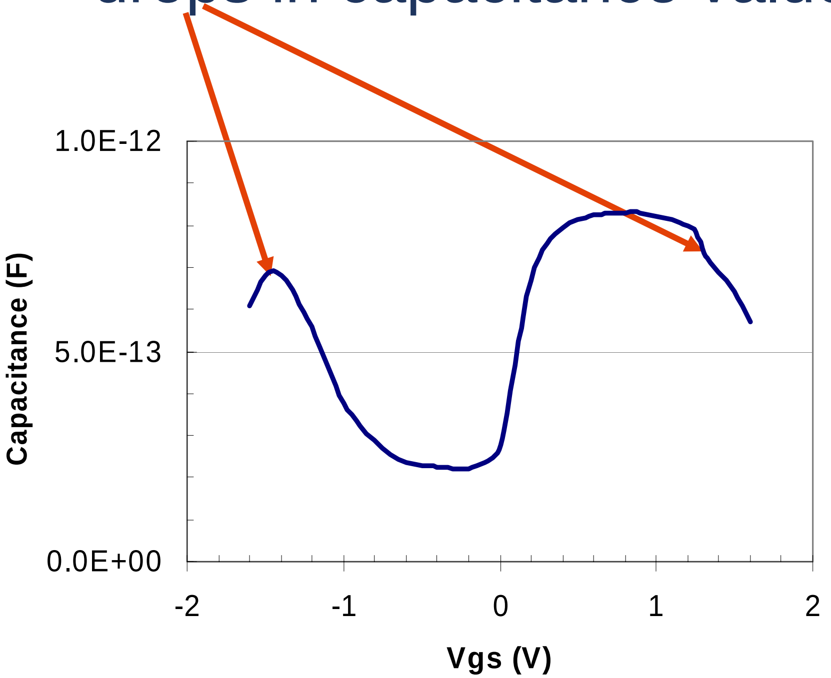
Into Reality

Content

1. Background
2. Measurement technique
3. Results
4. Design recommendation
5. Conclusions

Background

- What is the issue?
  - Traditional *C-V* measurement with the LCR meter (< 30MHz) is not accurate to extract gate oxide thickness with $J_G < \sim 100 A/cm^2$
  - When characterizing thin oxide, drops in capacitance values are observed!

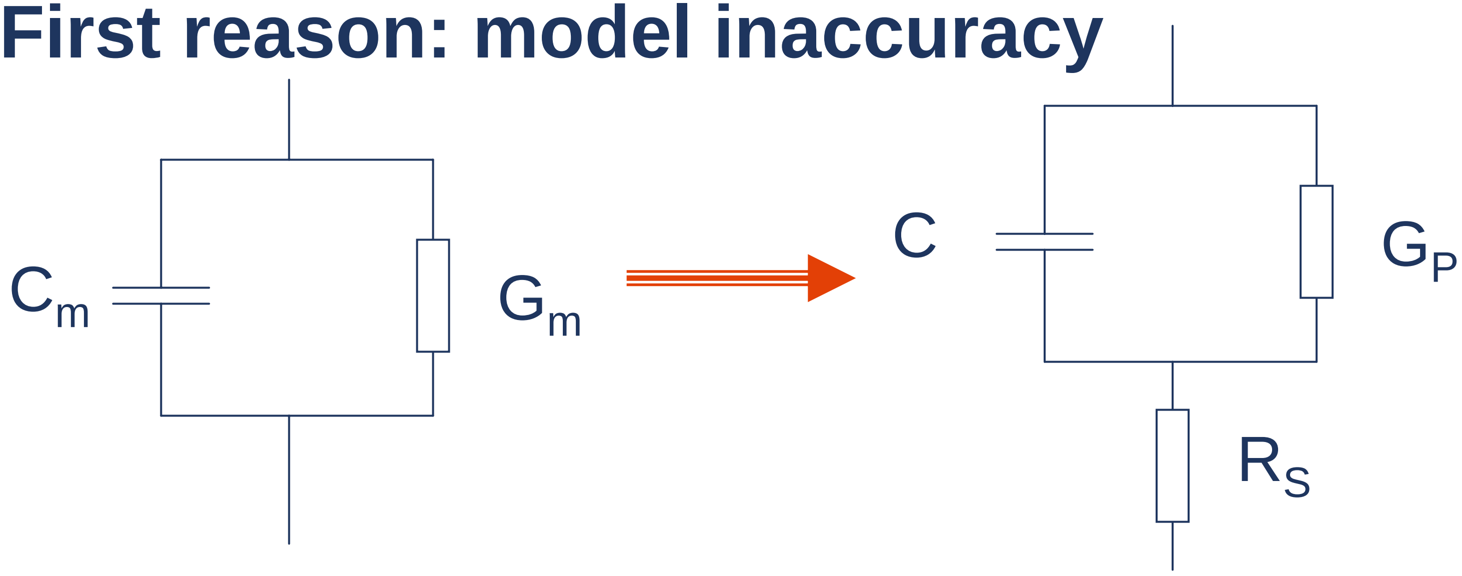


Why?

2 reasons

Background

1. First reason: model inaccuracy



C-G model

M-C-G model

$$\boxed{C_m = \frac{C}{(1 + R_S G_P)^2 + (\omega C R_S)^2}}$$

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Background

2. Second reason for the unsuccessful *C-V* on thin leaky oxide is :

The instrument precision!!!

$$\%error = 0.1\sqrt{1+D^2}$$

Henson, W.K *et al.*,
Elect. Dev. Lett. pp. 179-181 April 1999

Dissipation factor: $$\boxed{D = \frac{G_m}{2\pi f C_m} = \frac{1}{Q}}$$

t_{ox} ↓ C_m ↑ G_m ↑ *D* ↑

Background

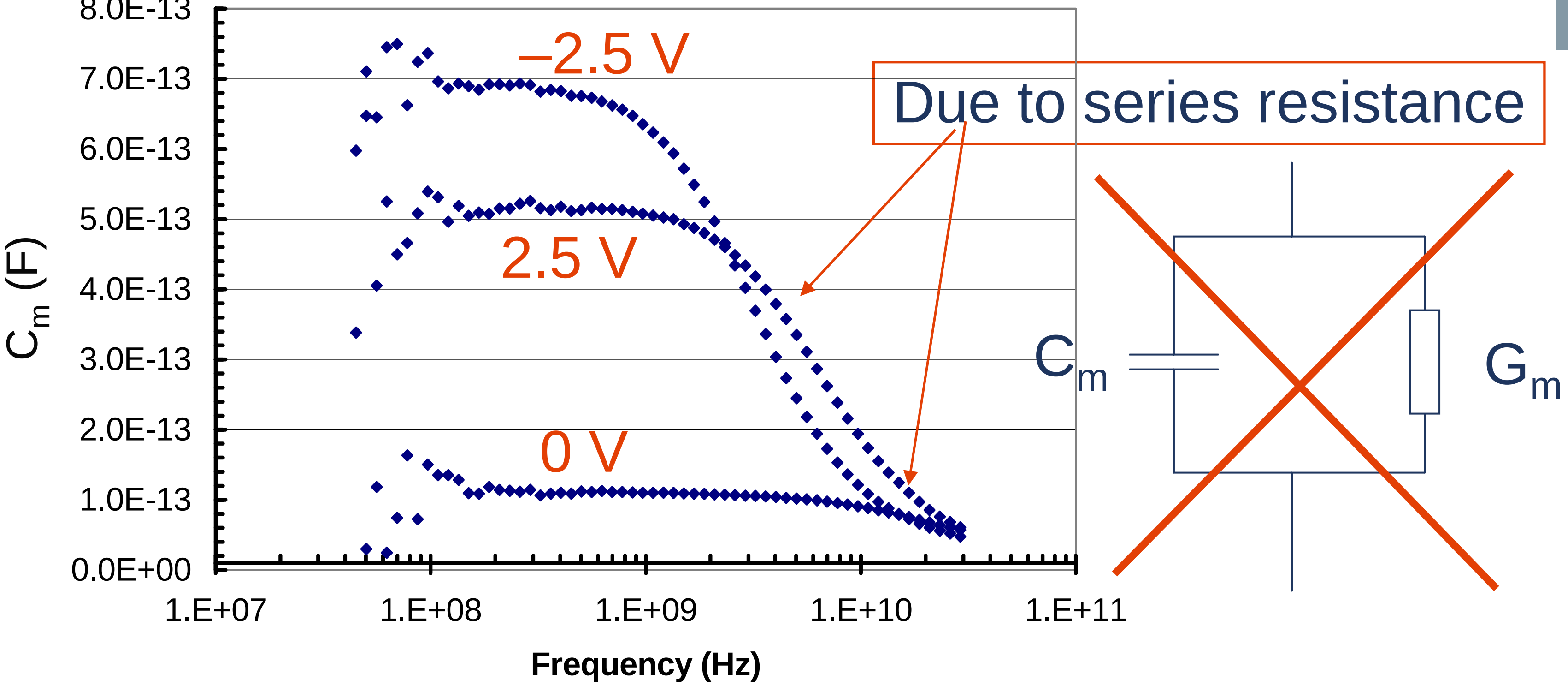
- J. Schmitz *et al.* introduced for the first time *CV* measurement *at RF frequency*. [ICMTS, pp.181-185, Mar’03]

From then on, what did we do?

- We further investigated the *C-V* characterization at RF frequency from 45MHz to 10GHz.
  - We proposed a measurement-frequency-selection technique.
  - By employing the 2FT to correct the series resistance we verified this by showing that the intrinsic capacitance can be obtained independent of the selected measurement frequency pairs.
  - We also demonstrated this technique on thin nitrided oxide with gate leakage current over 3kA/cm^2 at 2.5V.

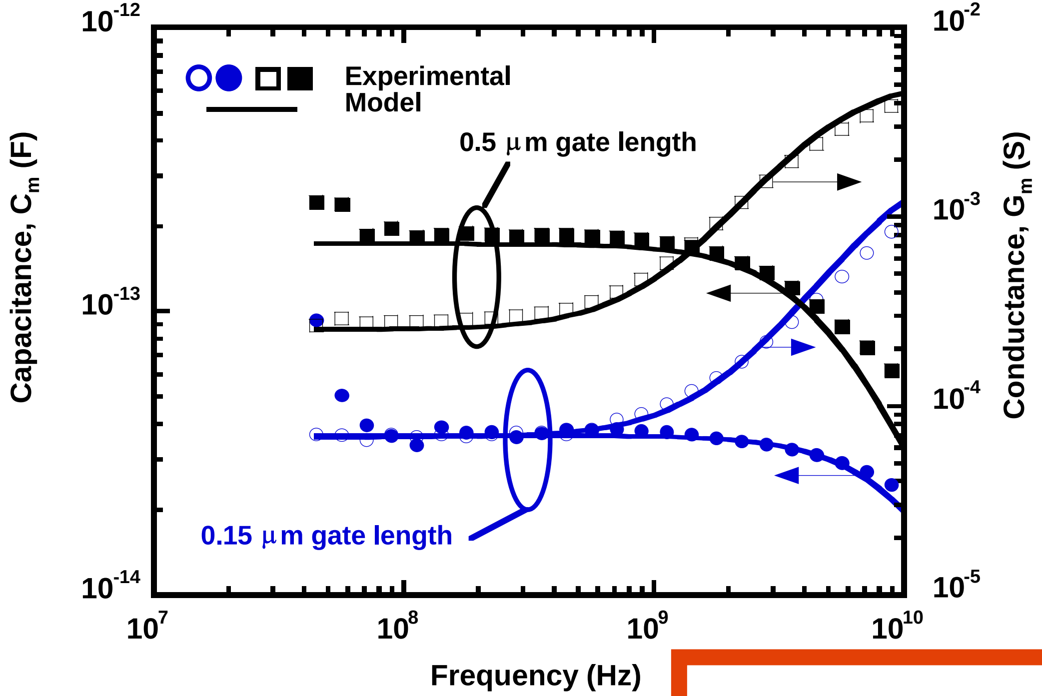
Measurement technique

- The measured capacitor is only bias dependent, but also frequency dependent as shown in the figure.

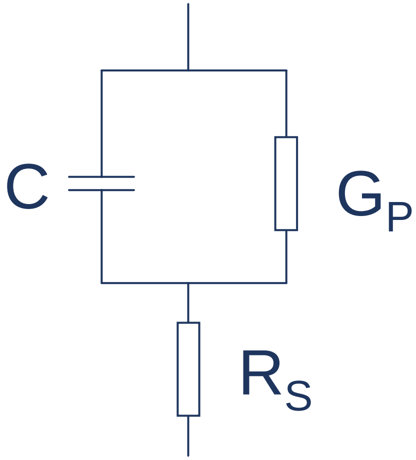


Due to series resistance

Measurement technique



M-C-G model



M-C-G model fits well the capacitance (C_m)&conductance (G_m) up to $\omega_C/3$ where

$$\omega_c = \frac{1+R_S G_P}{C R_S}$$

$$C_m = \frac{C}{\left(1+R_S G_P\right)^2 + (\omega C R_S)^2}$$

$$G_m = \frac{G_P(1+R_S G_P) + \omega^2 C^2 R_S}{(1+R_S G_P)^2 + (\omega C R_S)^2}$$

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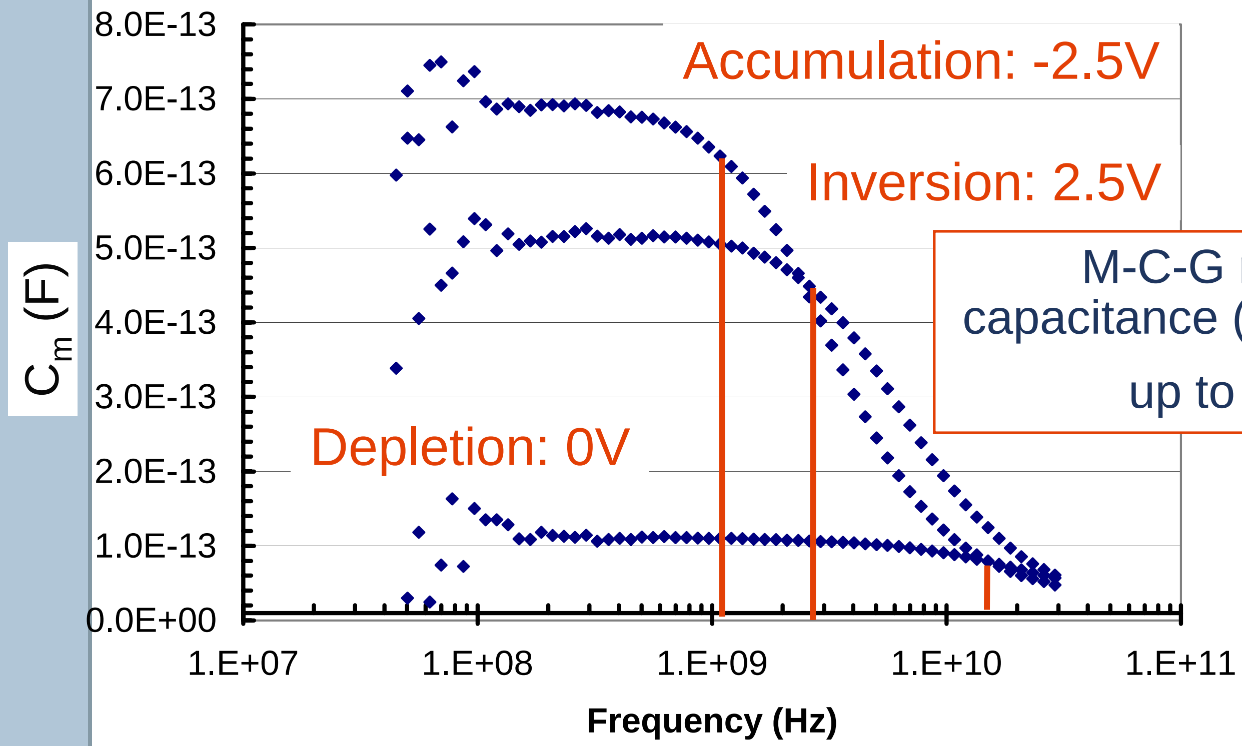
Measurement technique



M-C-G model fits well the capacitance (C_m)&conductance (G_m) up to $\omega_C/3$ where

$$\omega_c = \frac{1+R_S G_P}{C R_S}$$

- The M-C-G model fits well up to $\omega_C/3$, i.e. down to 10% of C_m.
- The accumulation region has the smallest ω_C due to high series resistance (R_S) and highest capacitance (C).
- Therefore the maximum measurement frequency is limited by the accumulation region.

Measurement technique

- Since the M-C-G fits well up to $\omega_C/3$ so the maximum measurement frequency can be set at this value.

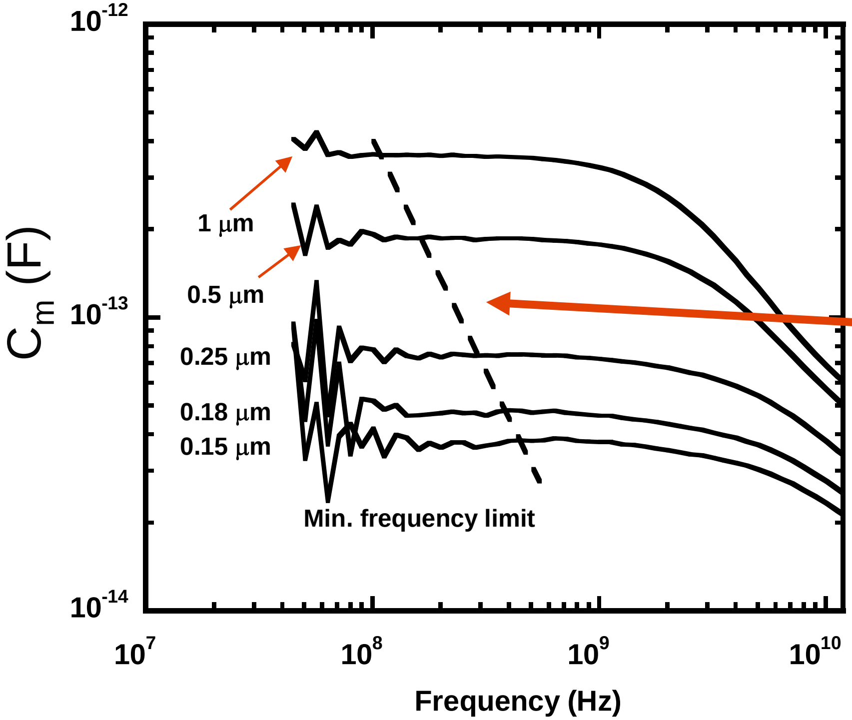
$$\boxed{f_{\max} = \frac{(1+R_S G_P)t_{ox}}{6\pi\varepsilon R_S WL}}$$

- Now we have the maximum measurement frequency estimation.

Is there minimum measurement frequency limit? …… in the next slides.

Measurement technique

- We observed that the lower frequency limit is determined by the impedance of the capacitance (C). The figure below shows the minimum frequency dependent on the gate areas.



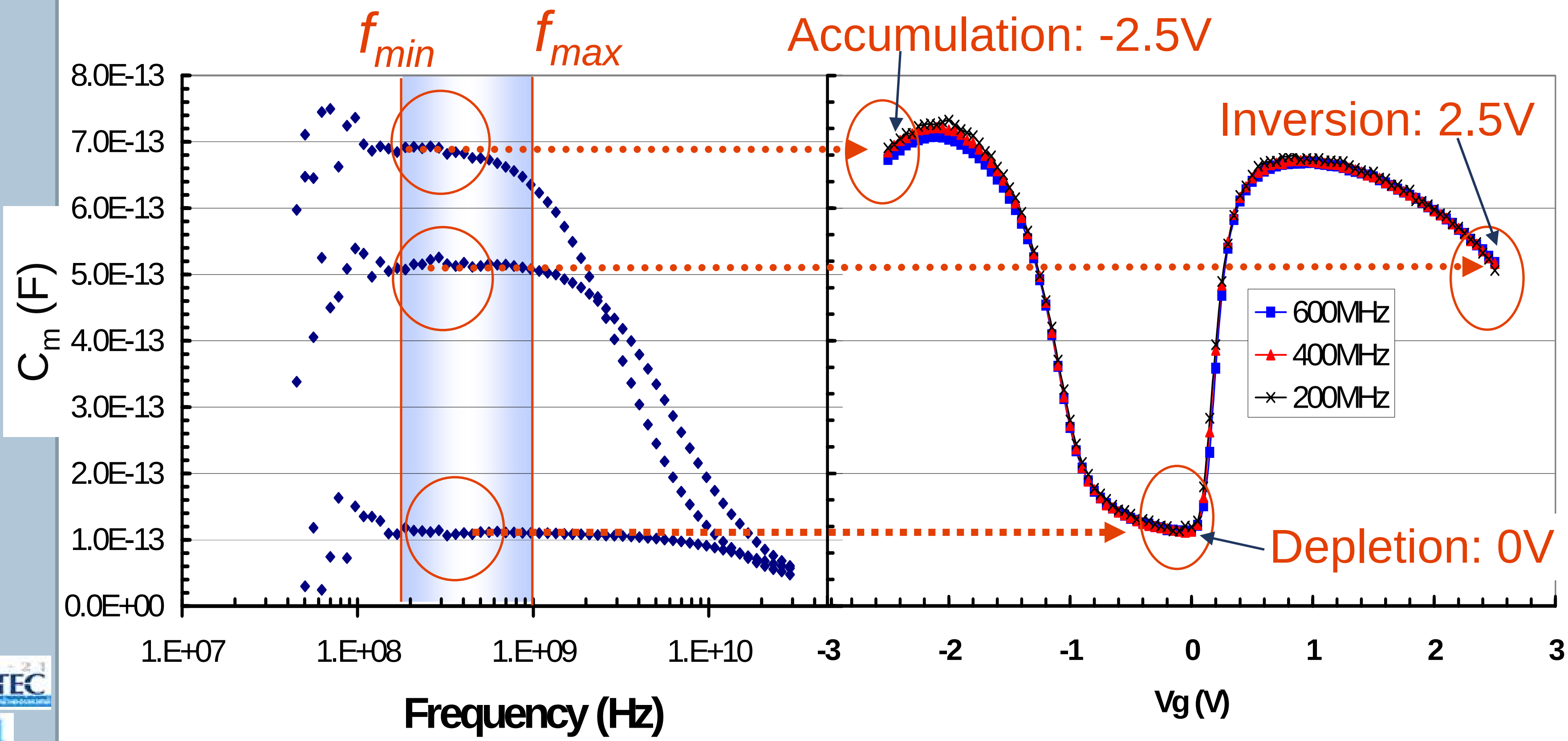
$$\boxed{f_{\min} = \frac{t_{ox}}{2Z\pi\varepsilon WL}}$$

- So we formulated a simple equation to estimate a minimum measurement frequency for our capacitance as shown above.

Measurement technique

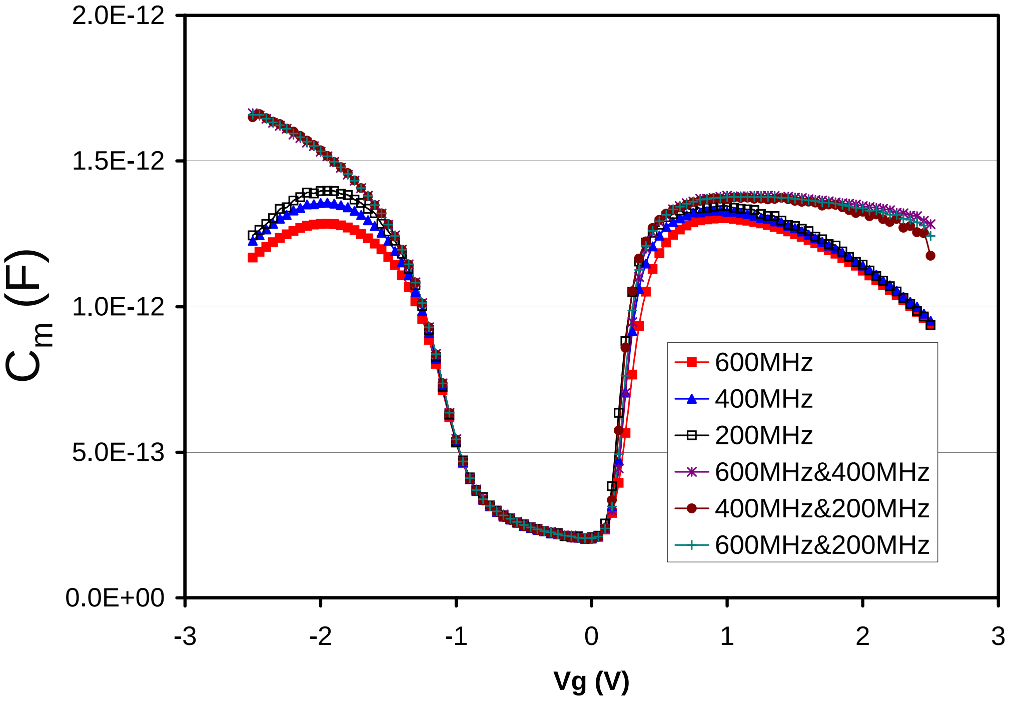
- Now we can explain why we sweep the frequency at the 3 biases!

This is to find out the measurement frequency range from the worst case, i.e. accumulation. Moreover is to check if we will have a reasonable *C-V* curve later.



Results

- With measurements of different frequencies we can apply the 2FT [3,4] to obtain the intrinsic capacitance value.
- The corrections are verified using three different frequency pairs yielding the same result.



[3] Yang, K.J. and C. Hu, Elect. Dev. Lett. pp.1500-1501, Jul.’99

[4] Nara, A. *et al.*, IEEE Trans. Semiconduc. Manuf., pp.209-213, May 2000.

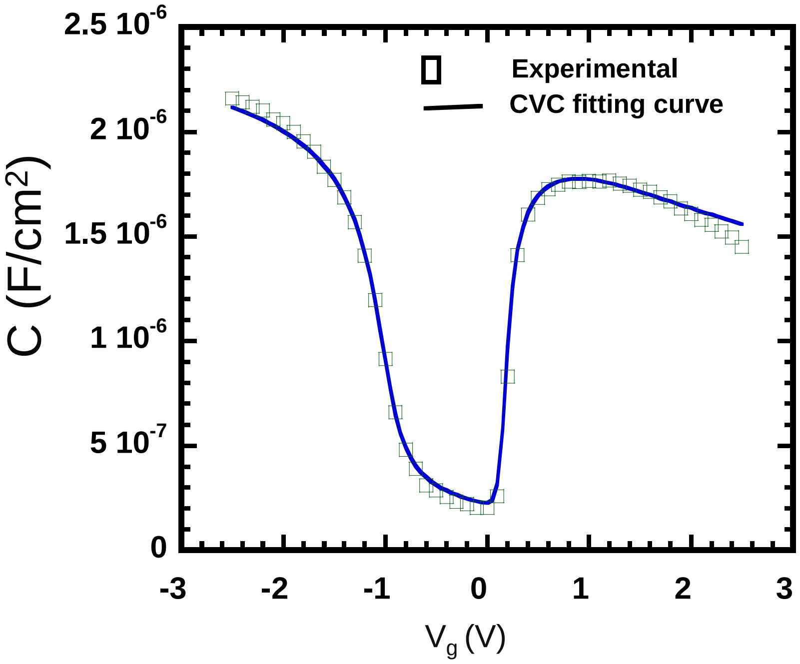
Results

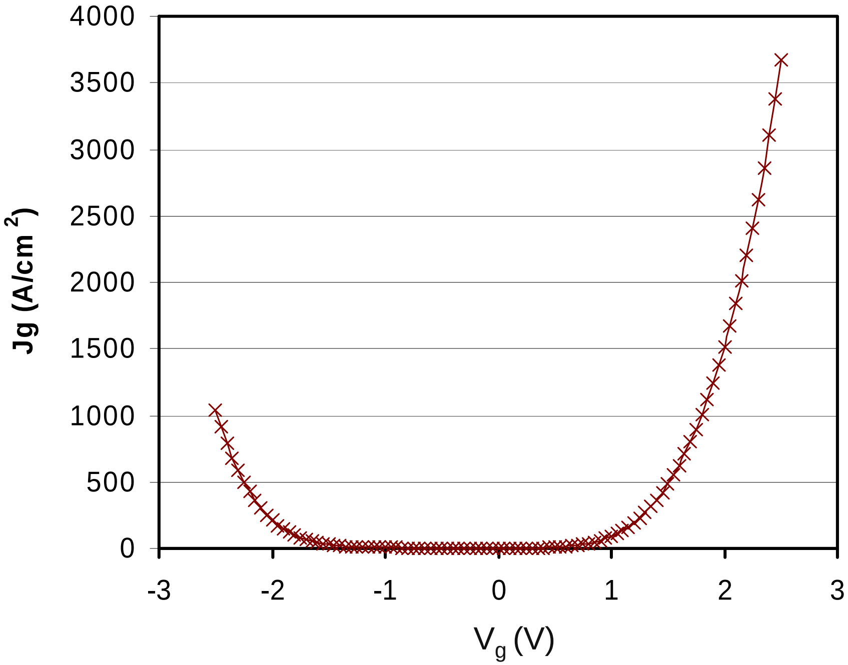
We demonstrated the measurement technique on

1.2-nm nitrided oxide with

J_g>3KA/cm^2@2.5V,

J_g>1KA/cm^2@-2.5V





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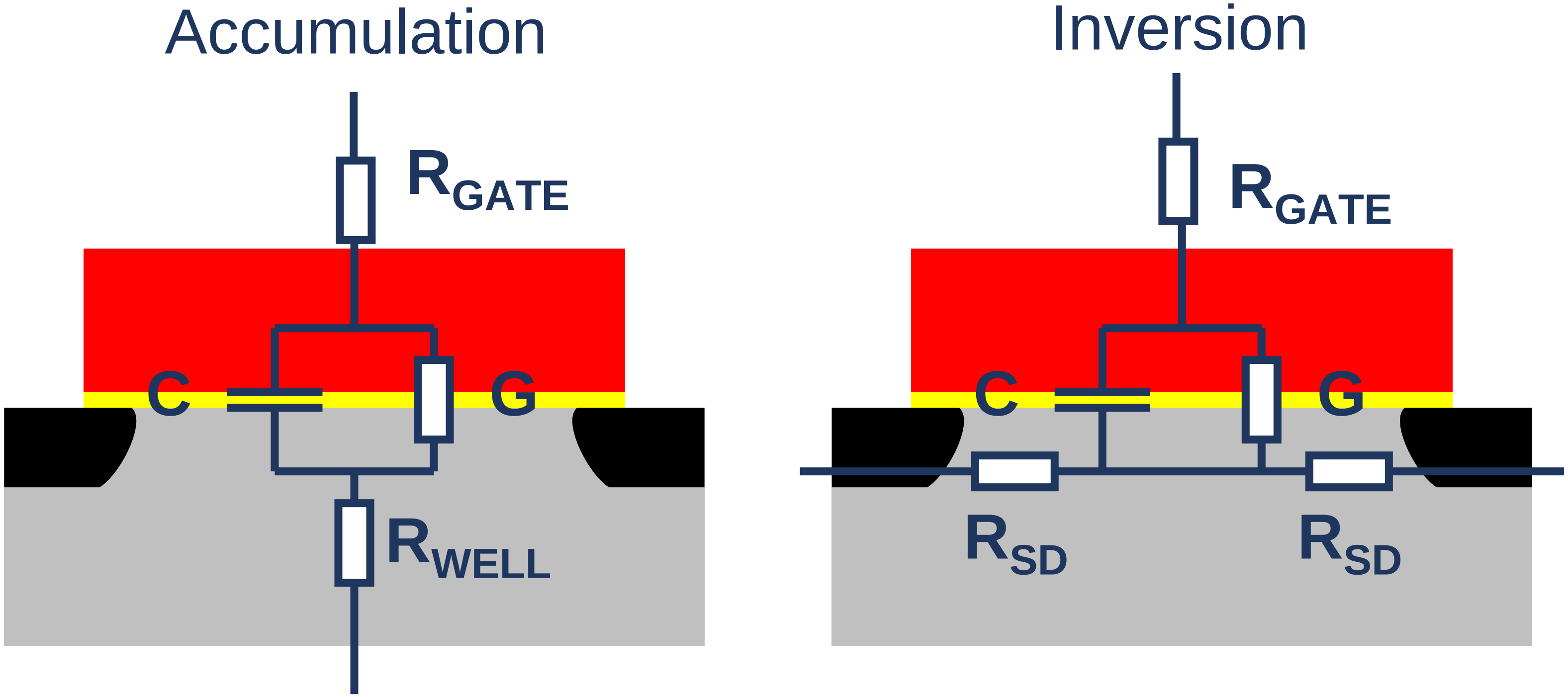
Design recommendation

- Series resistance in the M-C-G model is originated partly from source-drain to channel resistance (the well to channel resistance) in inversion (in accumulation) and partly from the gate resistance.



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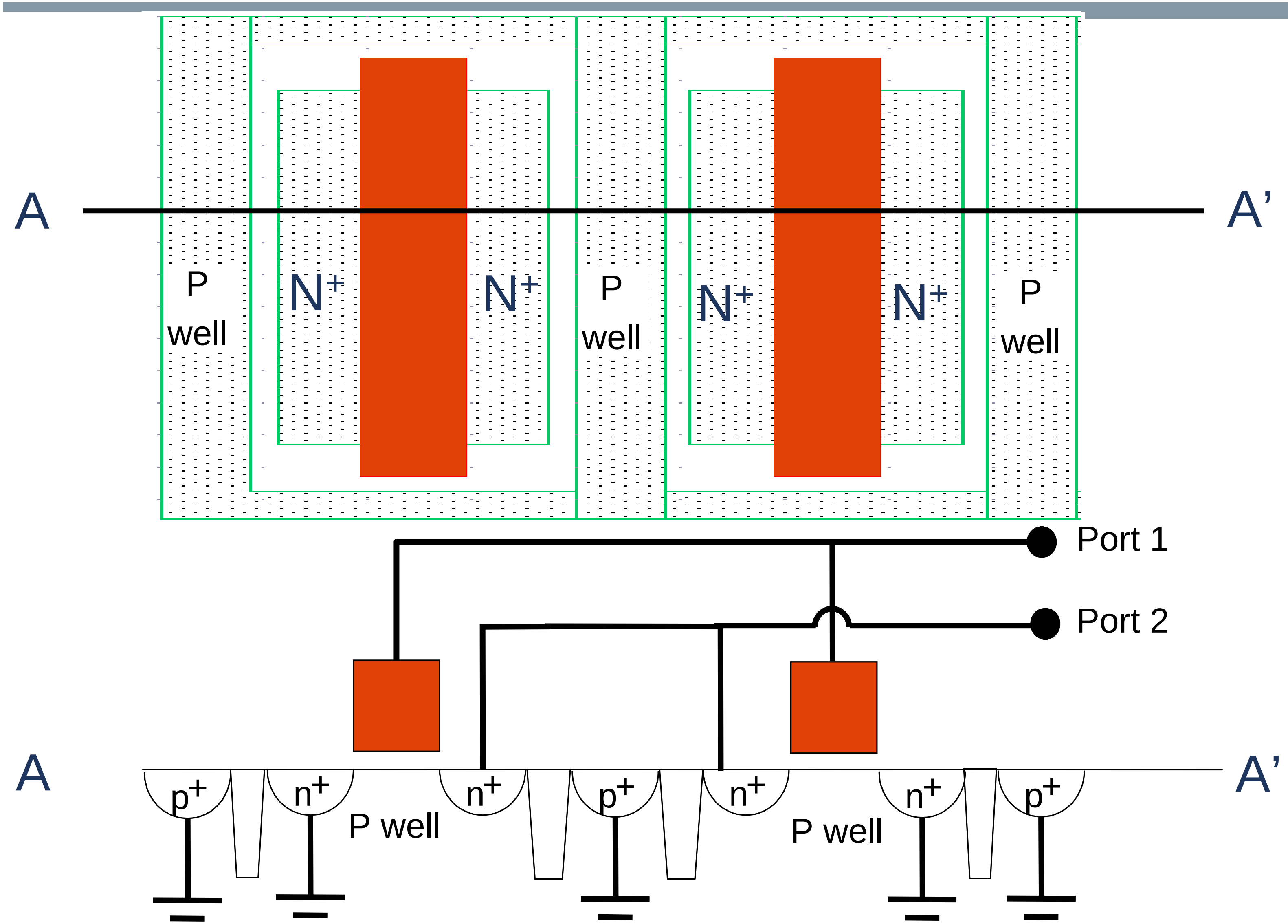
Design recommendation

- Even though we can correct the series resistance by employing the 2 frequency method, however only for moderate series resistance value (problem generally happens in accumulation region).

- Hence design the well connection as close as possible to the MOS channel area to reduce the series resistance (Very important in order to get the accumulation part of the *C*-*V* !!!).

See next slide….for instance.

Design recommendation



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Design recommendation

$$\boxed{f_{\min} = \frac{t_{ox}}{2Z\pi\varepsilon WL}}$$

$$\boxed{f_{\max} = \frac{(1 + R_S G_P)t_{ox}}{6\pi\varepsilon R_S WL}}$$

$$\boxed{C_m = \frac{C}{(1 + R_S G_P)^2 + (\omega C R_S)^2}}$$

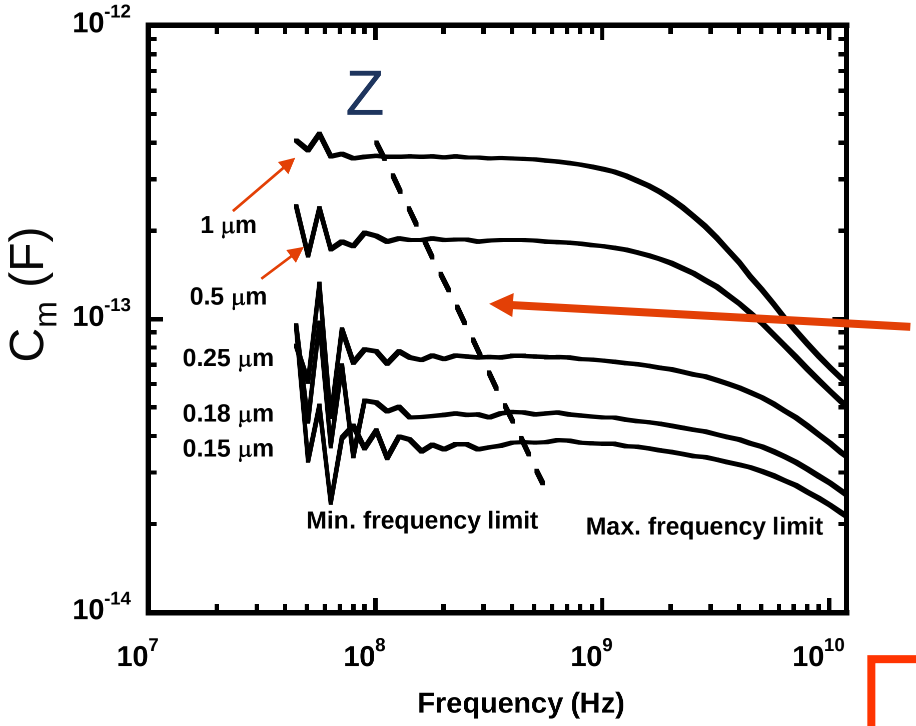
1. R_S should be kept small for wider measurement frequency range.
2. By use small gate length and keep the well connection as close as possible to the channel will ensure successful inversion and accumulation *C-V.*

Conclusions

1. We illustrated a 2-stepped frequency selection technique for RF frequency *C-V* measurement.
2. For moderate series resistance, we can use 2FT to extract the intrinsic *C-V*.
3. We successfully demonstrated the measurement on very thin nitrided oxide with Jg > 3KA/cm^2 (oxide thickness of 1.2nm).
4. We have also shown a test structure suitable for RF frequency *C-V* measurement.

Appendix 1
Minimum frequency limit observation

Z = Capacitive impedance



$$Z = \frac{1}{\omega_{\min} C}$$

$$Z = \frac{1}{2\pi f_{\min} C}$$

$$Z = \frac{t_{ox}}{2\pi f_{\min} \varepsilon WL}$$

$$\boxed{f_{\min} = \frac{t_{ox}}{2Z\pi\varepsilon WL}}$$

Appendix 2
Maximum frequency limit observation

$$When: \omega_c C R_S = 1 + R_S G_P$$

$$\omega_{\max} = \frac{\omega_c}{3} = \frac{1 + R_S G_P}{3 C R_S}$$

$$2\pi f_{\max} = \frac{1 + R_S G_P}{3 C R_S}$$

$$f_{\max} = \frac{1 + R_S G_P}{6\pi C R_S}$$

$$\boxed{f_{\max} = \frac{(1 + R_S G_P) t_{ox}}{6\pi R_S \varepsilon W L}}$$

Appendix 3
2 Frequency technique (2FT)

$$Z = R_S + \frac{R_P(1 - j\omega C R_P)}{1 + \omega^2 C^2 R_P^2}$$, M-C-G model

$$Z = \frac{D_m - j}{\omega C_m (1 + D_m^2)}$$, C-G model

$$D_m = \frac{G_m}{\omega C_m}$$

$$\frac{1 + \omega^2 C^2 R_P^2}{C R_P^2} = \omega^2 C_m (1 + D_m^2)$$

From [3] Kevin, J. Yang and Chenming Hu, IEEE Trans. pp.1500-1501, July '99.

$$\boxed{C = \frac{f_1^2 C_{m1}(1 + D_{m1}^2) - f_2^2 C_{m2}(1 + D_{m2}^2)}{f_1^2 - f_2^2}}$$

$$R_P = \frac{1}{\sqrt{\omega^2 C_m C (1 + D_m^2) - \omega^2 C^2}}$$

$$R_S = \frac{D_m}{\omega C_m (1 + D_m^2)} - \frac{R_P}{1 + \omega^2 C^2 R_P^2}$$