Federal University of Santa Catarina
Department of Electrical Engineering
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Modeling and Parameter Extraction of Zero-VT MOSFETs for Ultra-Low-Voltage Operation

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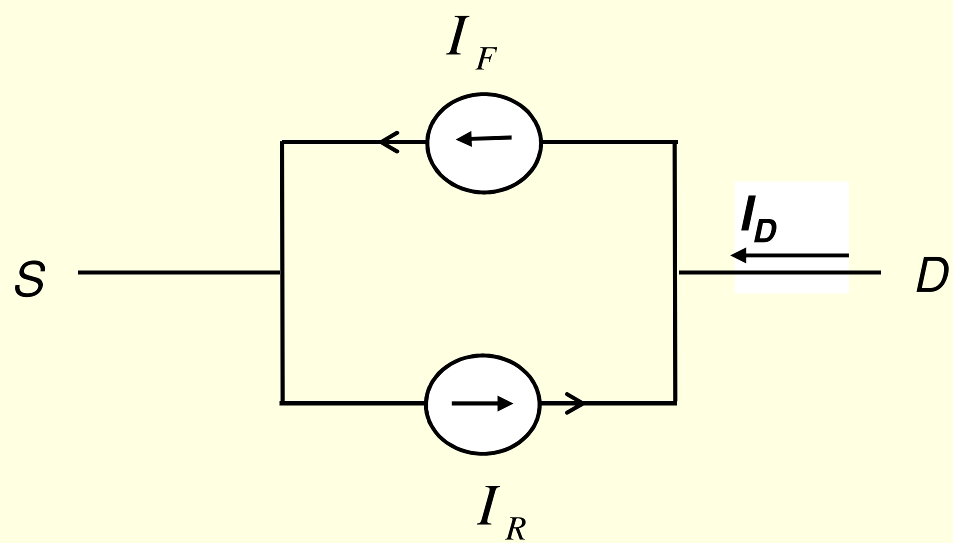
Outline

- ⇨ **MOSFET model in weak inversion & triode regions**
- ⇨ **Low voltage operation of the basic amplifiers**
- ⇨ **Zero-VT MOSFETs**
- ⇨ **Colpitts oscillators**

MOSFET: Weak inversion (WI) model



$$V_P \cong \frac{V_G - V_{T0}}{n}$$

$$I_D = I_F - I_R = I_0 \left(e^{\frac{V_P - V_S}{\phi_t}} - e^{\frac{V_P - V_D}{\phi_t}} \right)$$

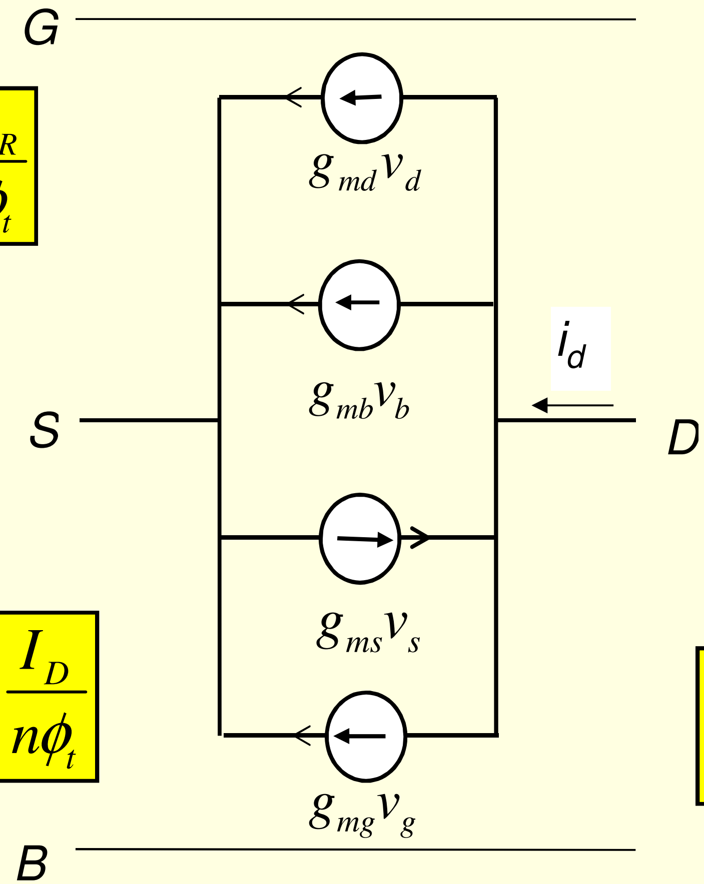
$$\phi_t = \frac{kT}{q} (= 26 \text{ mV @ 300K})$$

n: slope factor (= 1.05 - 1.1 for zero-VT transistors),

V_P *:* pinchoff voltage; V_{T0}*:* threshold voltage

MOSFET: low-frequency small-signal model in the triode region

$$g_{md} = \frac{I_R}{\phi_t}$$

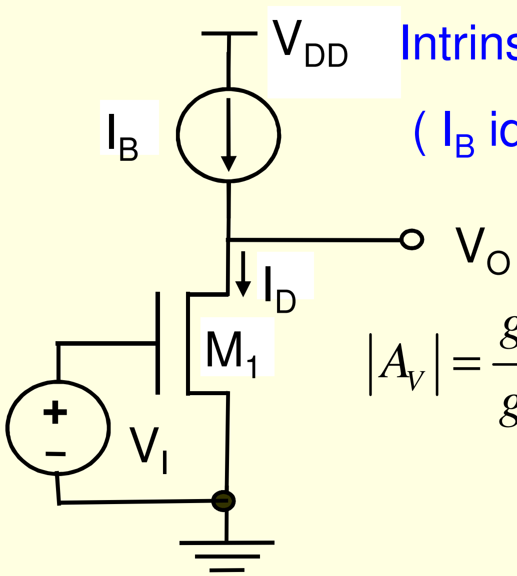


$$g_{mg} = \frac{g_{ms} - g_{md}}{n} = \frac{I_D}{n\phi_t}$$

$$g_{ms} = \frac{I_F}{\phi_t}$$

$$g_{ms} = g_{mg} + g_{mb} + g_{md}$$

Low-voltage operation of the common-source amplifier



Intrinsic gain stage

(I_B ideal current source)

$$|A_V| = \frac{g_{mg}}{g_{md}} = \frac{g_{ms} - g_{md}}{n g_{md}} = \frac{1}{n}\left(\frac{g_{ms}}{g_{md}} - 1\right)$$

weak inversion operation

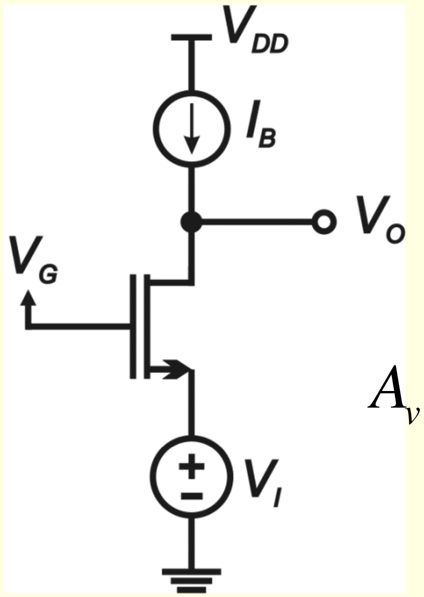
$$\frac{g_{ms}}{g_{md}} = e^{\frac{V_{DS}}{\phi_t}}$$

$$|A_V| = \frac{1}{n}\left(e^{\frac{V_{DS}}{\phi_t}} - 1\right)$$

or

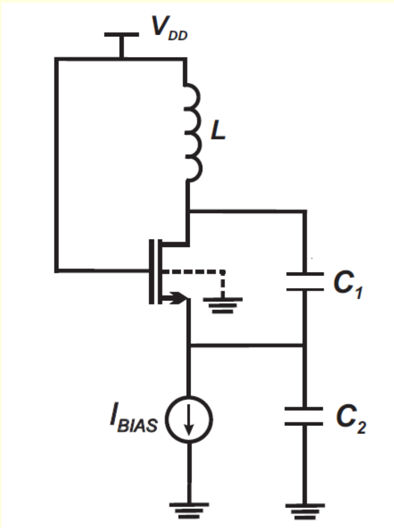
$$V_{DS} = \phi_t \ln\left(1 + n|A_V|\right)$$

Low-voltage operation of the common-gate amplifier



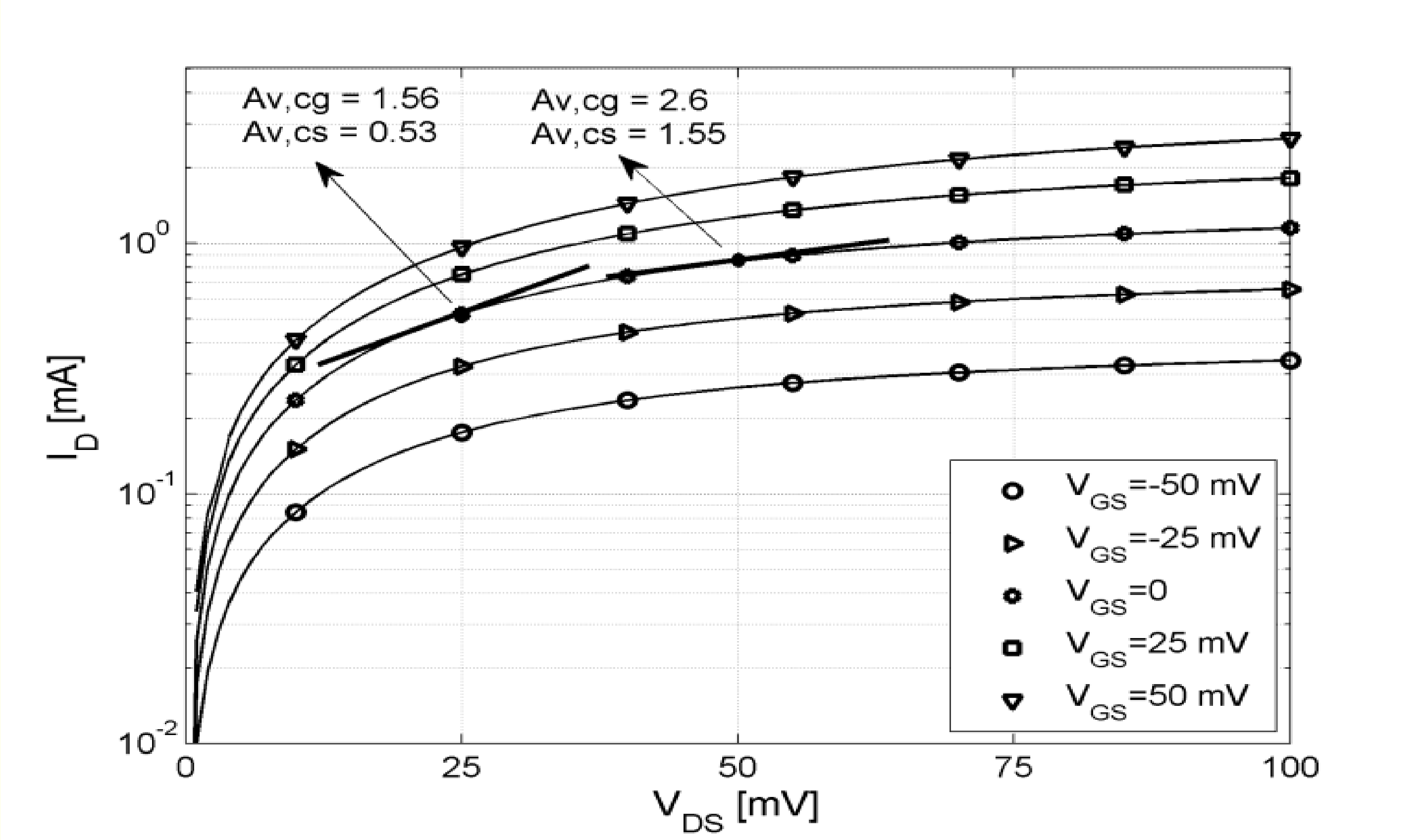
$$A_{v,cg} = \frac{v_o}{v_i} = \frac{g_{ms}}{g_{md}} = e^{\frac{qV_{DS}}{kT}}$$

The common-gate amplifier provides a voltage gain of greater than unity for $V_{DS}>0$. → Very useful property for lowering the supply voltage limit for the operation of oscillators (later).



Common- gate Colpitts oscillator

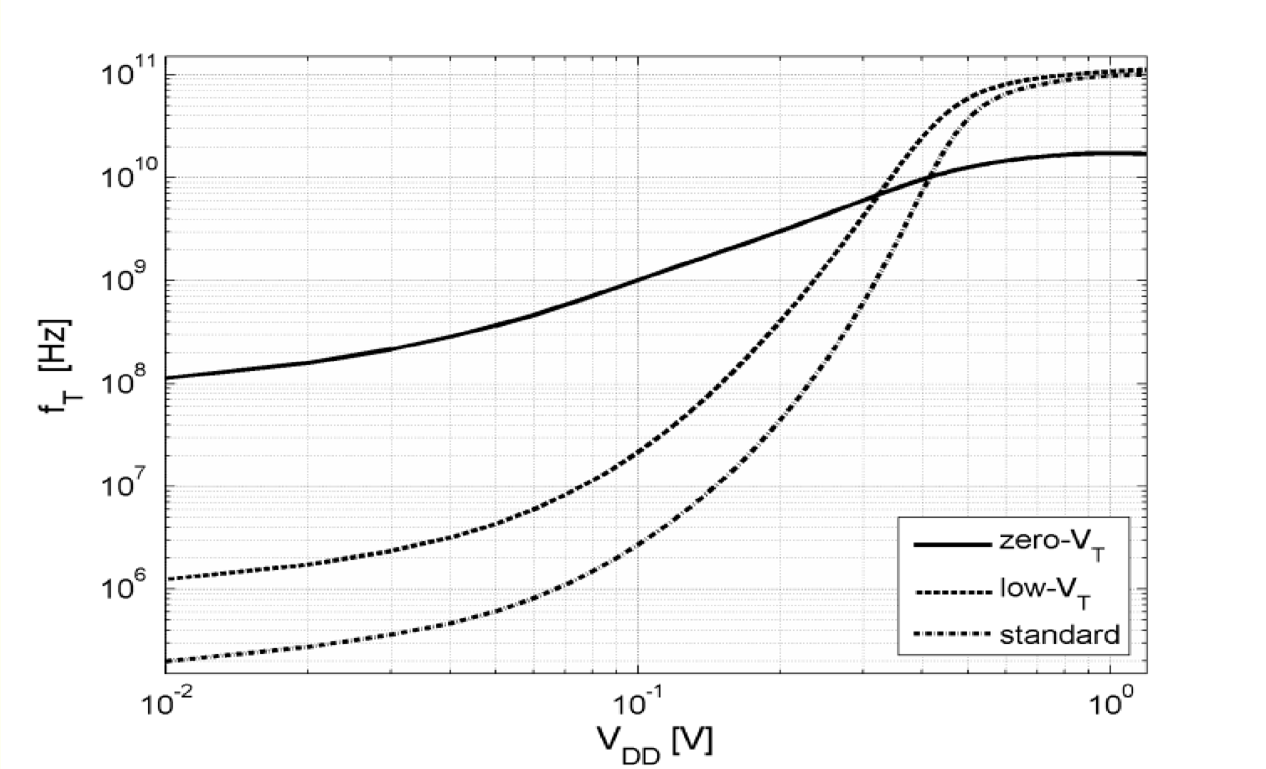
Zero-VT MOSFETs - 1



- I_D x V_{DS} (V_S=V_B) characteristics for a zero-VT transistor with W/L=2500µm/420nm. The values of the common-gate and common-source gains are 1.56 and 0.53, respectively, for V_{GS}= 0 V and V_{DS}= 25 mV.

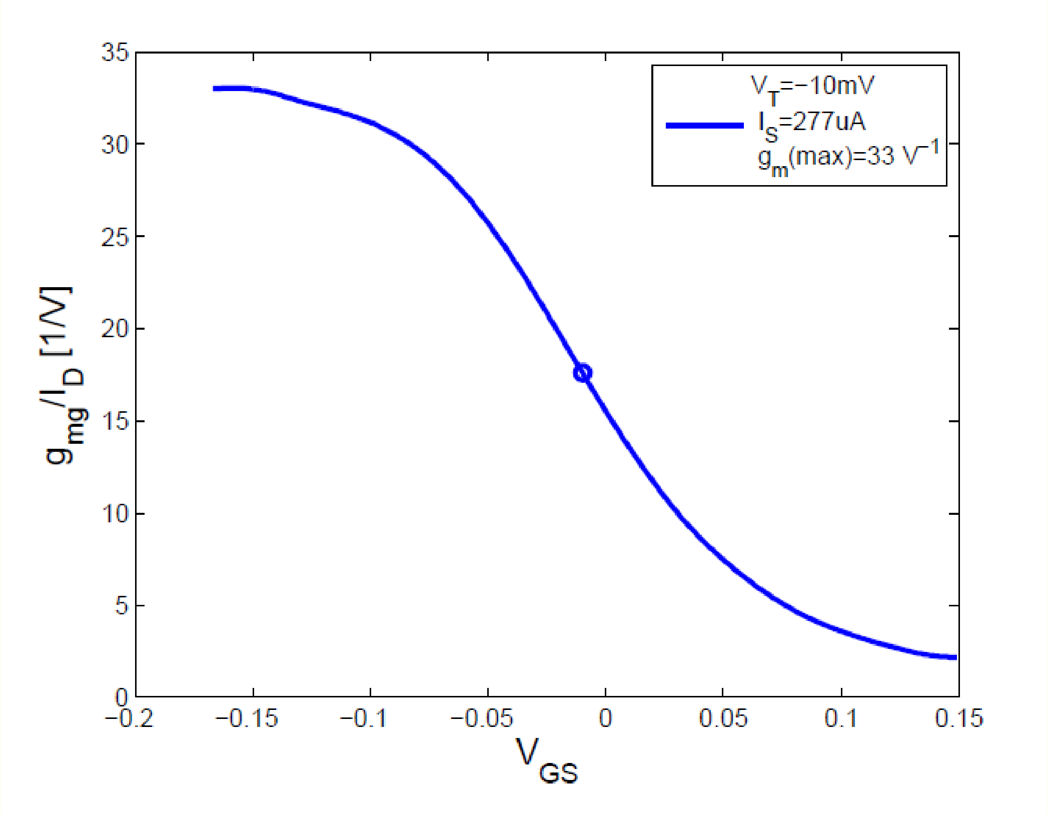
Zero-VT MOSFETs - 2

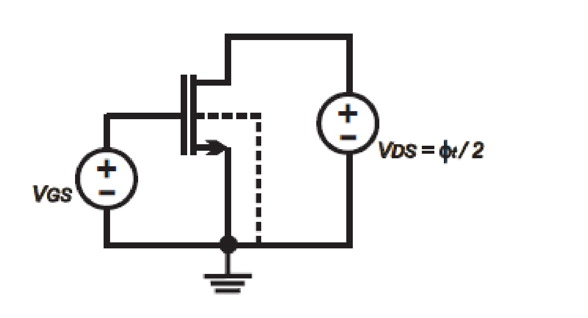
- .



- First order approximation of the intrinsic cutoff frequency of the zero-VT (W/L=3µm/0.42µm), low-VT (W/L=0.84µm/0.12µm), and standard transistors (W/L=0.84µm/0.12µm) of a 0.13 µm CMOS technology. The transconductance g_m was simulated for V_S=V_B=0, and V_D=V_G=V_{DD}.

Zero-VT MOSFETs - 3

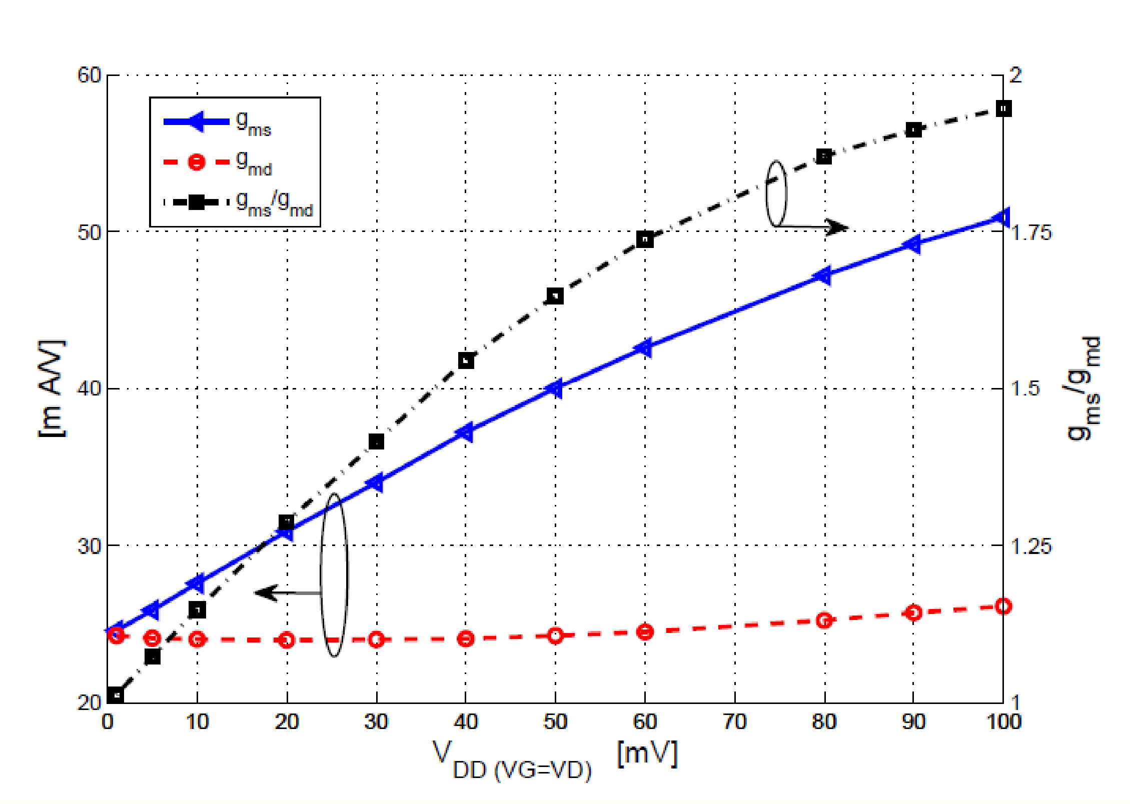


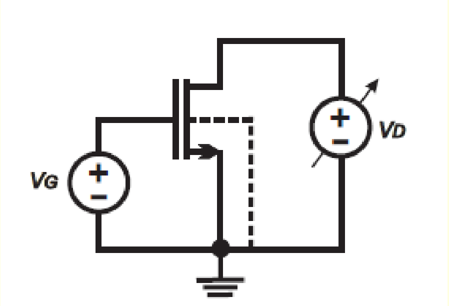


Circuit configuration for measuring the g_{mg}/I_D characteristic in the linear region

Experimental g_{mg}/I_D characteristic for a transistor with W/L = 2500 µm/0.42 µm

Zero-VT MOSFETs - 4

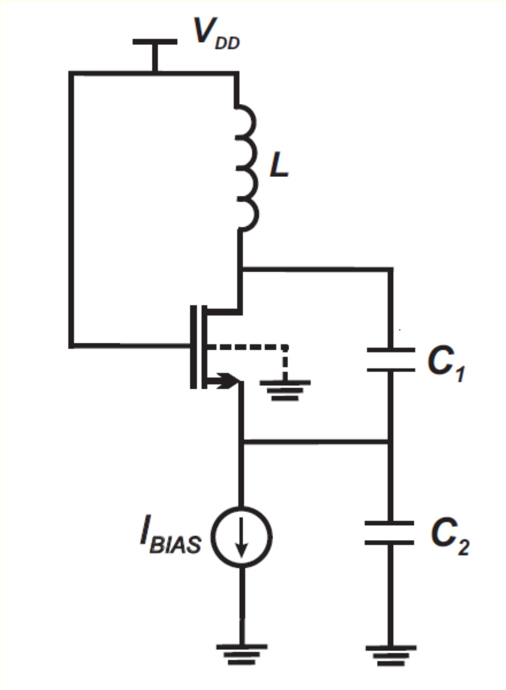


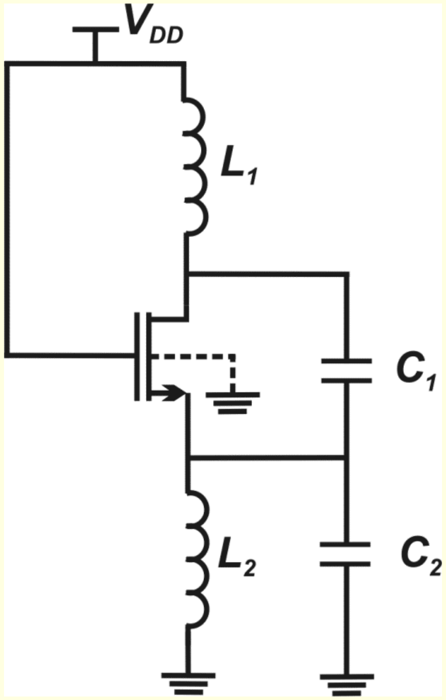


Circuit configuration for measuring g_{md}

g_{ms}, g_{md} and g_{ms}/g_{md} as functions of V_{DD} for a transistor with W/L = 2500 µm/0.42 µm

Colpitts oscillators



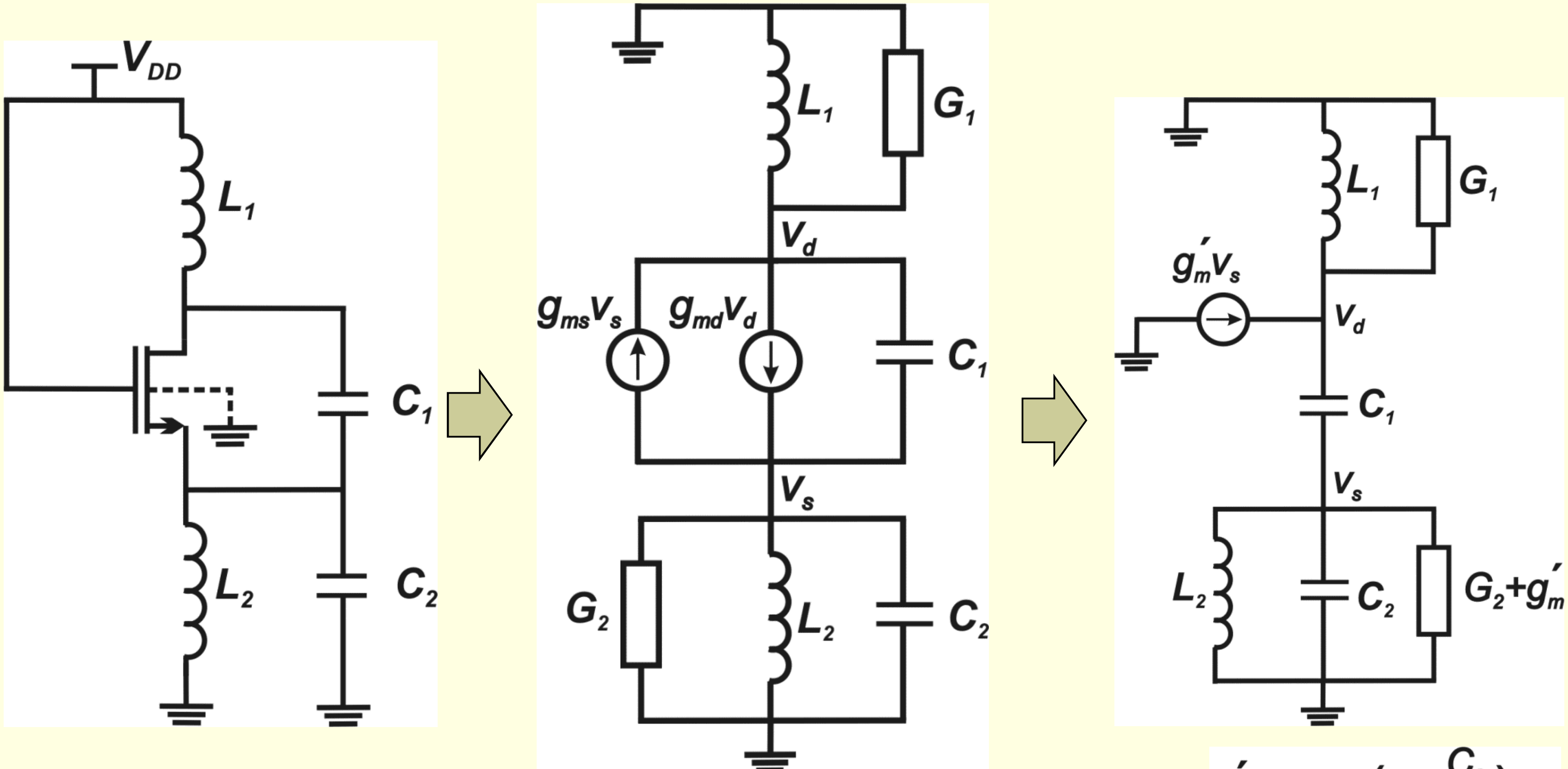


Conventional Colpitts oscillator

Enhanced swing Colpitts oscillator (ESCO) *

* T. W. Brown et al, *IEEE JSSC*, Aug. 2011.

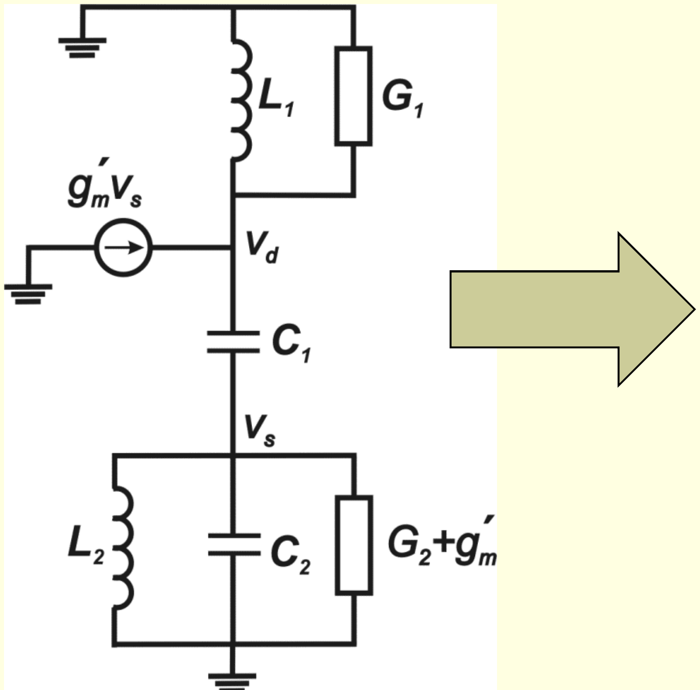
ESCO: small-signal model 1

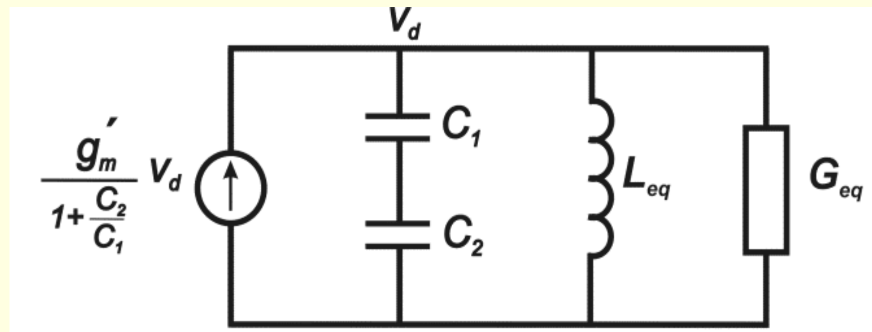


$$g'_m = g_{ms} - \left(1+\frac{C_2}{C_1}\right) g_{md}$$

$$v_s \cong \frac{v_d}{1+\frac{C_2}{C_1}} \rightarrow g_{ms} v_s - g_{md} v_d \cong g'_m v_s$$

ESCO: small-signal model 2

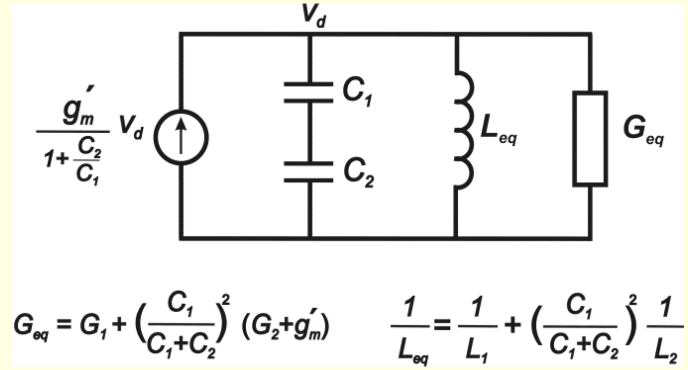




$$G_{eq} = G_1 + \left(\frac{C_1}{C_1+C_2}\right)^2 (G_2+g_m') \qquad \frac{1}{L_{eq}} = \frac{1}{L_1} + \left(\frac{C_1}{C_1+C_2}\right)^2 \frac{1}{L_2}$$

Second-order small-signal model of the ES Colpitts oscillator.

ESCO: start-up condition



$$g_{ms} > \left(1+\frac{C_2}{C_1}\right) g_{md} + \frac{C_1}{C_2} G_2 + \left(2+\frac{C_1}{C_2}+\frac{C_2}{C_1}\right) G_1$$

Optimum value of capacitors to minimize g_{ms} (for the conventional Colpitts $g_{md} = G_2 = 0$!)

$$\frac{C_2}{C_1} = \sqrt{\frac{G_1+G_2}{g_{md}+G_1}}$$

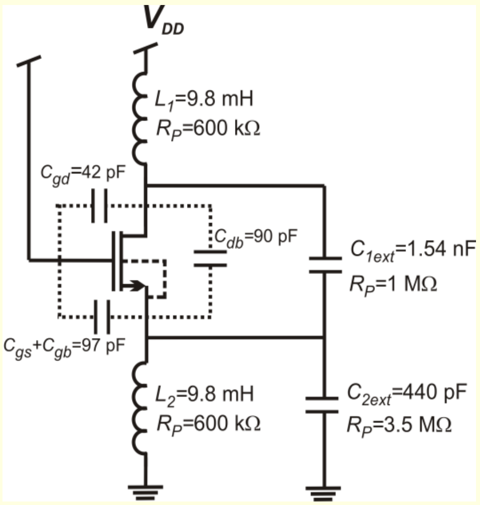
For ideal inductors (and capacitors) $G_1 = G_2 = 0$

$$g_{ms} > \left(1+\frac{C_2}{C_1}\right) g_{md}$$

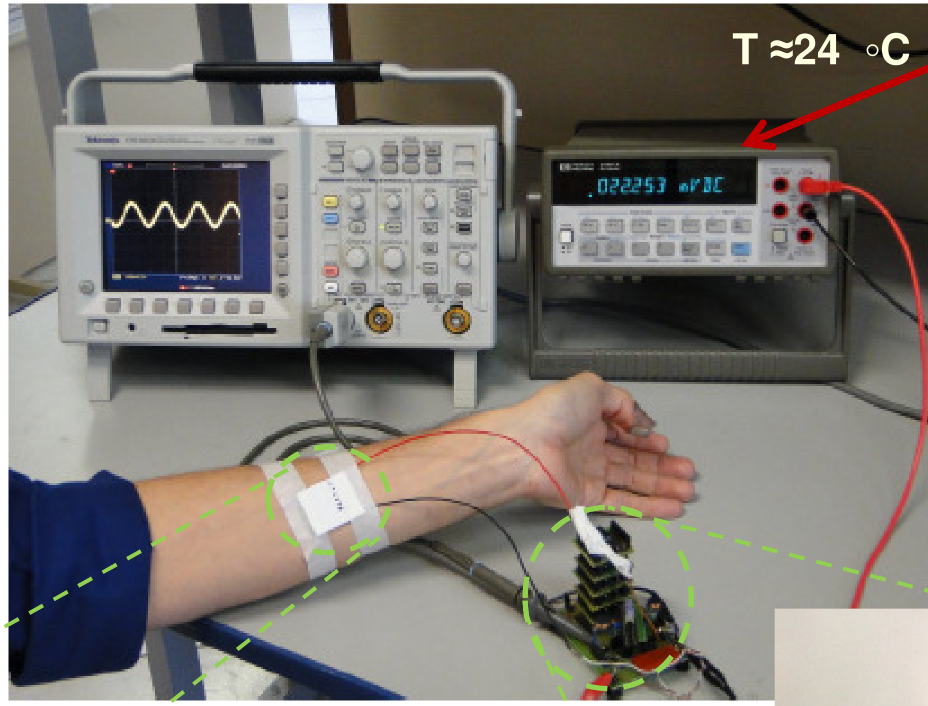
$$V_{DD\lim} = \frac{kT}{q} \ln\left(1+\frac{C_2}{C_1}\right)$$

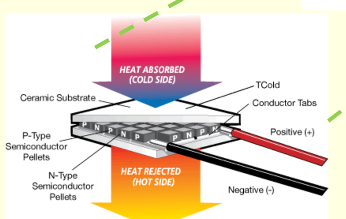
Colpitts oscillator: first prototype

Powered by a thermoeletric generator



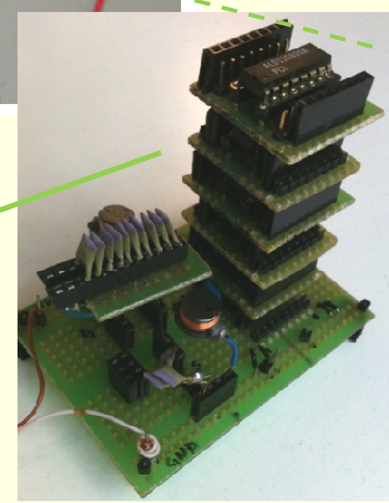
V_{DD}=22.2 mV





thermoelectric generator

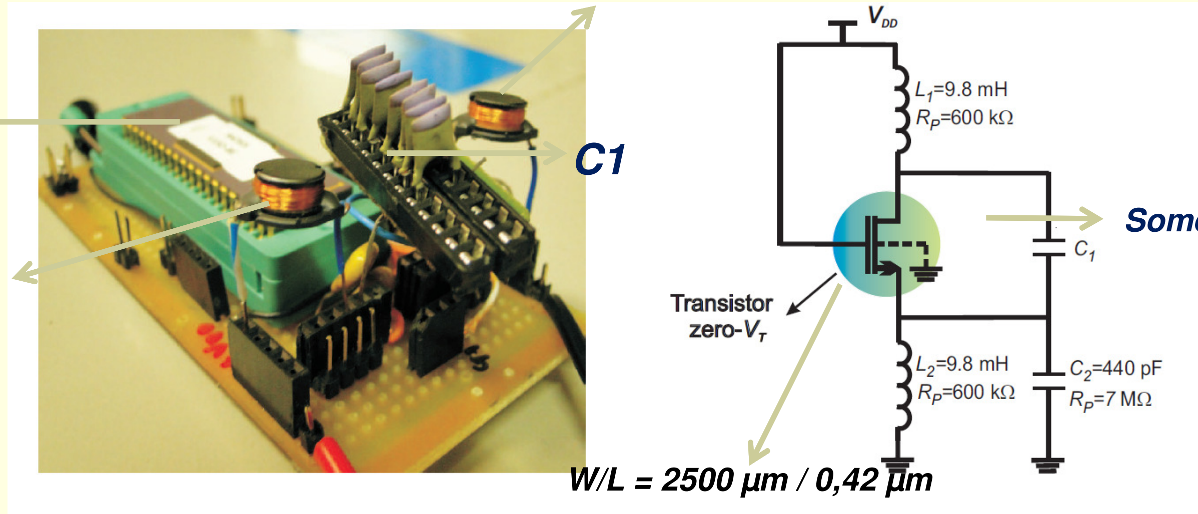
24 // NMOS
***Zero-VT** (ALD 1108)*
VT=59 mV, IS=11.2 uA



Colpitts oscillator: second prototype

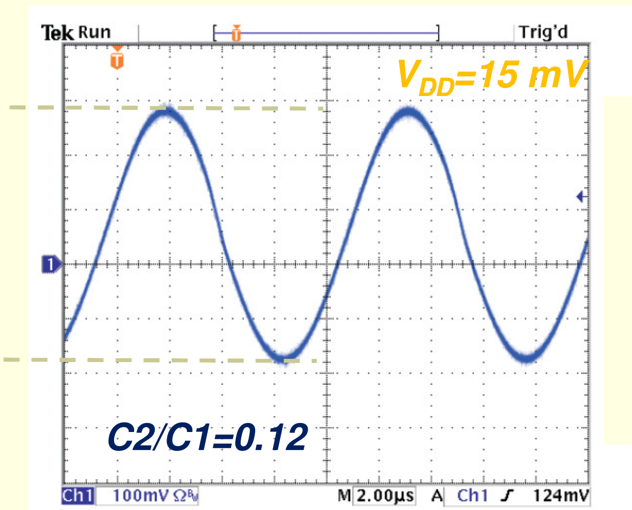
Vdd < 20 mV

Zero-VT
IBM 130 nm



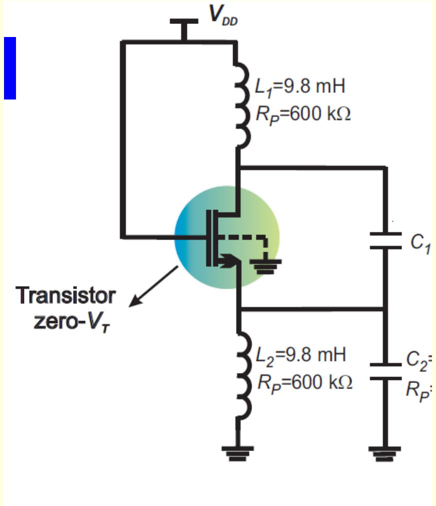
Some values

V_{PP}≈440 mV

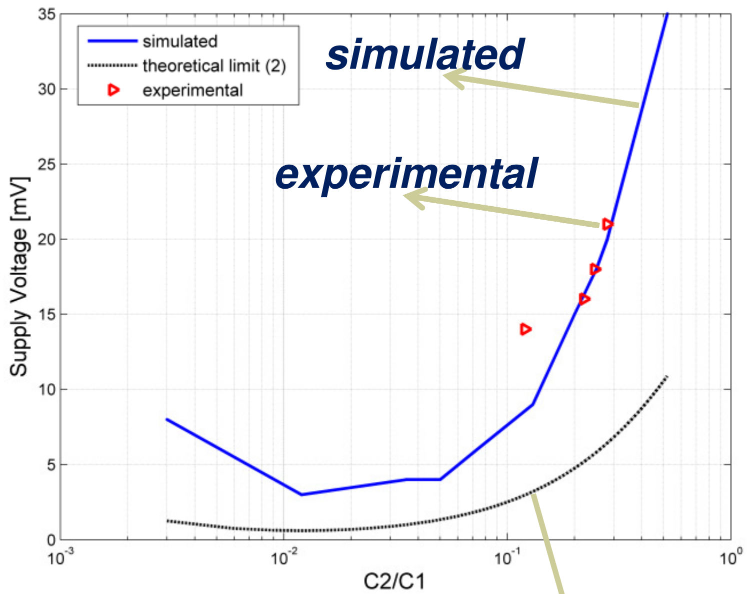


f_{osc}≈110 kHz
V_{DD}=15 mV

Second prototype: experimental results



$V_{DD,min}$ x C2/C1



simulated

experimental

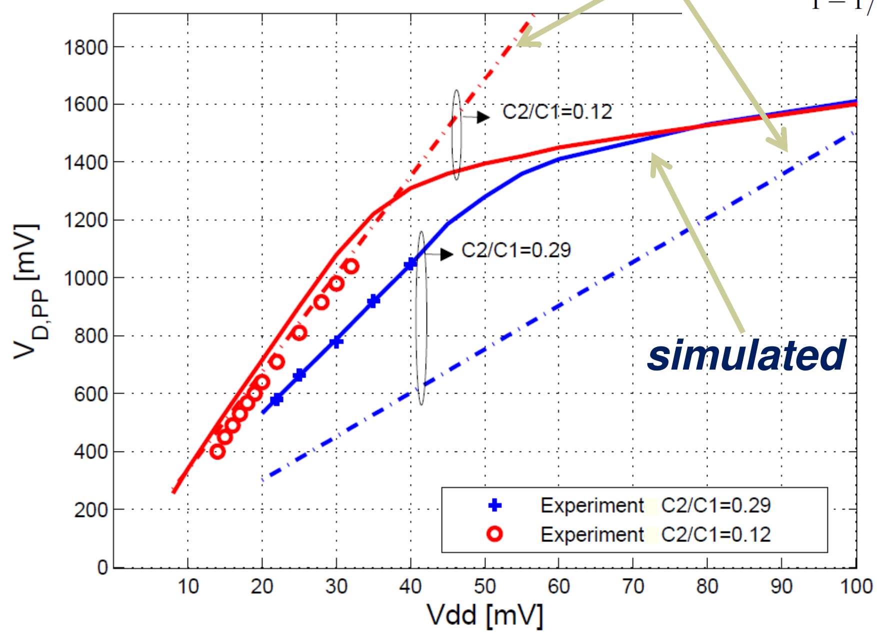
f_{osc}≈110 kHz

weak inversion

V_{PP} x V_{DD}

calculated

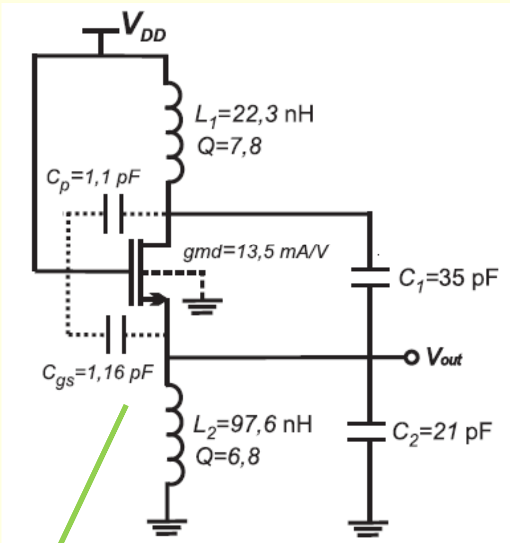
$$A_{d,max} = \frac{V_{DD}}{1-1/a}$$



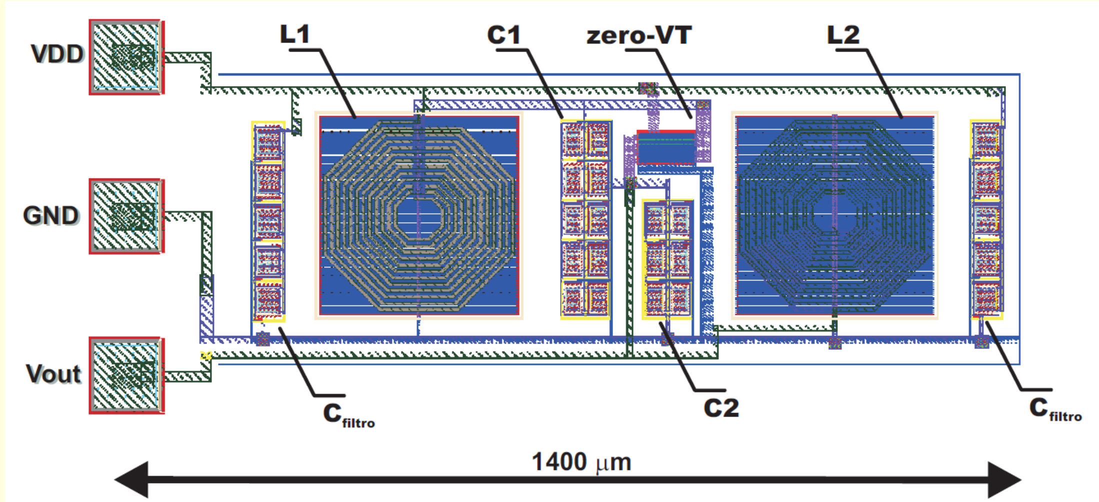
simulated

Colpitts oscillator IC: simulation results

Design : f=300 MHz



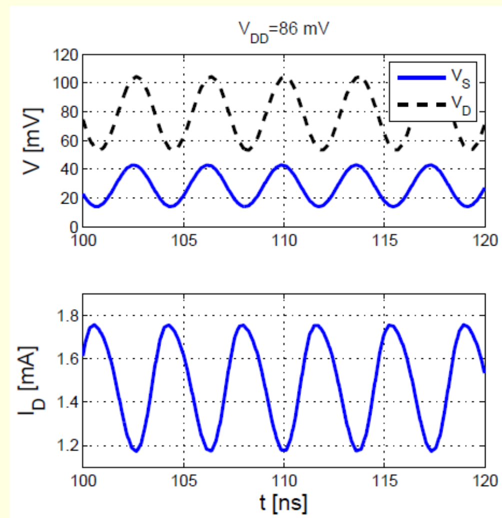
W/L = 2500 µm / 0,42 µm



Results ***(Simul. from layout)***

Designed f	**300 MHz**
f	262 MHz
$V_{DD,min}$	86 mV
$V_{S,PP}$	23 mV
$V_{DD,max}$	650 mV

(Vdd=86 mV)



Summary

- **There is no V_{DD} hard limit for low voltage operation of analog MOS circuits (oscillators can operate with supply voltage values below kT/q)**
- **The ideal active device for low voltage operation is characterized by small footprint and high drive capability at low supply voltages → MOSFETs with threshold voltage ~ 0 V are excellent choices for ULV operation**
- **The charge-based MOSFET model is very convenient for the design of ultra-low-voltage circuits (operation in triode region/ WI)**

References

- F. R. de Sousa, M. B. Machado, C. Galup-Montoro, " A 20 mV Colpitts Oscillator powered by a thermoelectric generator", *ISCAS 2012*.
- C. Galup-Montoro, M. C. Schneider, and M. B. Machado, "On the ultra-low-voltage operation of CMOS analog circuits: amplifiers, oscillators, and rectifiers', to appear in IEEE TCAS II.