MOS CAP Analysis

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***Abstract*—Abstract — The main aim of this report is to explain and analyze the capacitance variation of the two terminal Ptype substrate MosCap. the analysis includes deriving the threshold and the charge concentration variation and the charge profile of the various biasing states.**

***Index Terms*—**$\Phi_{ms}, \varphi_s s, \varphi_{ox}, \varepsilon_s, \varepsilon_{ox}, t_{ox}, V_T, V_t, V_{fb}, V, E_s, E_{ox}, q, N_a, Q_d, Q_{dinv}, Q_s, Q_f$

I. Introduction

AS miniaturization and scaling are increased in the semiconductor domain it is important to understand the semiconductor devices behaviour at the sub-micron level. So the scaling down of the semiconductor devices, is no longer allows to use the of conventional passive devices in the submicron circuits. Capacitor one of the leading passive element, realizing capacitor in the semiconductor devices is a hot topic in the tech world. since MosFET is the most used semiconductor devices in today's tech world, it is good to analyze the Capacitor behaviour the most. This report mainly discusses the construction, energy band diagrams and the threshold of the MosCap.

II. Capacitance Voltage characteristics of the Two terminal MOSFET

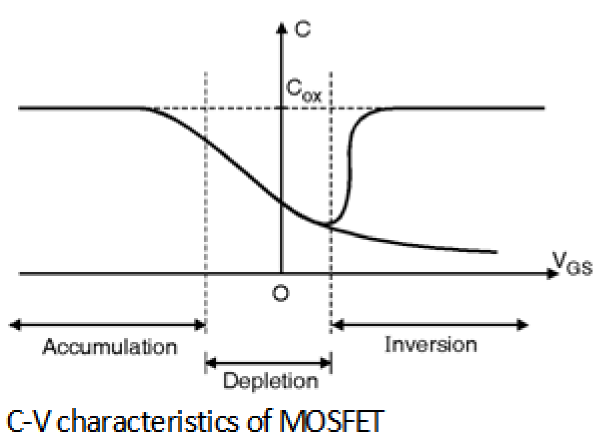

Fig. 1. Capacitance Voltage variation plot of the two terminal MosCap

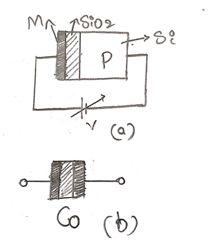

Fig. 2. Construction of the two terminal MosCap
a. MosCap , b. Normalized metal to metal cap

III. Construction of the Two terminal MoSCap

Fig[2] shows the constrictions of the two terminal MoSCap, a dielectric material ***SiO*** is sandwiched between the highly doped Metal and the Silicon substrate. The is Metal terminal called the Gate and the silicon terminal is the Substrate, a gate can be a highly doped poly-silicon also.

IV. Analysis of the Ideal Two terminal MoSCap

A. Conditions for the ideal MoSCap

- The work function of the metal and the semiconductor is zero $\Phi_{\mathrm{ms}} = 0$, perfectly a flat band condition.
- Oxide trapped charges Q_{ot}, fixed charges at the edge of oxide and the surface contact of the silicon Q_f, mobile charges at the surface of the silicon Q_m all are zero.

B. Ideal Two Terminal MoSCap biasing and the behavior

*1) Negative bias $V < 0$; **Accumulation**:* Fig.[3] if the applied voltage $V < 0$, negative charges acquire at the gate since the two-terminal mos is having the capacitor construction the corresponding the positive charges start to accumulate at the surface of the silicon since the holes are the majority carriers in the silicon it is easy to accumulate the positive charges at the surface, this state is called accumulation sate.

*2) Negative bias $V_{fb} < V \simeq 0$; **Weak Accumulation / Depletion**:* Fig. [4] when the applied V voltage slightly above the flat band voltage yet to define the flat band voltage, for the explanation purpose just assume it is the large negative voltage and nearly to the zero, the negative charges at the

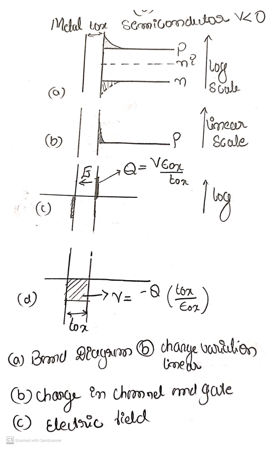

Fig. 3. MosCap Accumulation $V << 0$

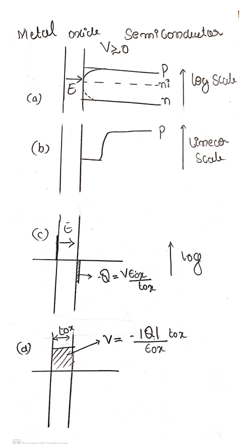

Fig. 4. MosCap Depletion $V_{fb} < V + 0$

gate start to decrease and the corresponding positive charges start to deplete, and the negative charges start piling up in the silicon. since the silicon is p-type and the holes are the majority carriers, for small negative voltage or approximate to zero. the majority of carriers start to deplete in the silicon, the applied voltage is not so strong to accumulate the majority carriers in the silicon, this state can be realized as the weak accumulation or the depletion state.

3) Positive bias $0 < V < V_T$ *; **Depletion / Weak Inversion**:* Fig.[5] the applied voltage is $0 < V < V_T$, the gate acquire the positive charges and the respective negative charges start piling up at the silicon surface, a movable negative charges form a stream of charges at the surface of the silicon, this stream can call it as the channel. A depletion layer is created between the channel mobile charges and majority charges in the silicon, as the applied vertical electric field increase the minority carries in the silicon is almost equal to the majority carries in silicon and we can say that both minority and the majority charge carriers are approached to the intrinsic charge level of the silicon. The mobile minority carries stream (channel) is very weak, this status is the weak inversion of the MosCap.

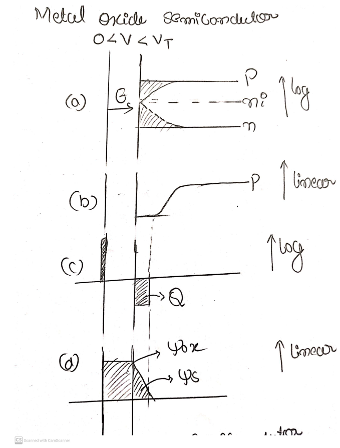

Fig. 5. MosCap Depletion / Weak inversion $0 < V < V_T$

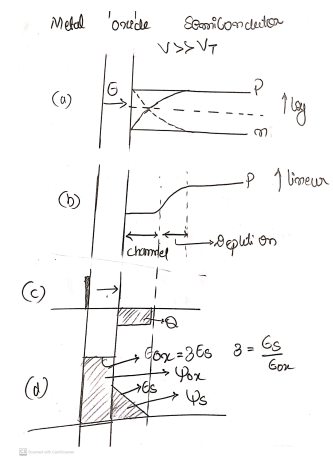

Fig. 6. MosCap Strong Inversion $V >> V_T$

4) Poistive bias $V >> V_T$ *; **Strong Inversion**:* Fig. [6] for the larger applied positive voltage the majority carries in the channel is completely depleted, and the minority carriers in the silicon becomes equal to the majority carries, the channel formed by a strongly inverted charges in the silicon.

5) Summery of the ideal MosCap biasing : Fig. [7] the carrier concentration in the silicon is changes based on the applied voltage Fig.[7]. a is the flat band condition at the $V = 0$ (assumed $V_{fb} = 0$) there is no charge variation.As the negative voltage increases at the gate, the majority carriers are accumulated, and the applied voltage gradually increases towards the positive voltage the majority carries are pushed away and the majority carriers energy band start to bend down. Minority carriers are more and more piling up at the surface of the silicon. As the applied voltage more and more positive the minority carries approach intrinsic carrier level of the silicon, this voltage is the threshold voltage of the MosCap, for

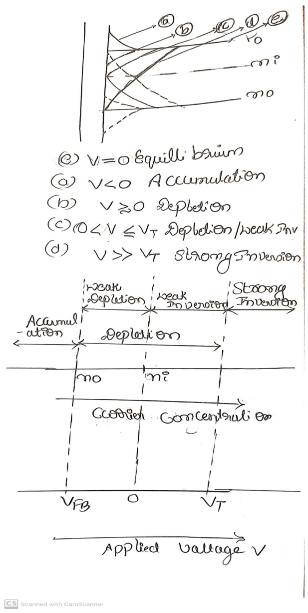

Fig. 7. summery of the MosCap biasing and the carrier concentration variation

the positive voltage beyond the threshold the minority carrier concentration equals the majority carriers in the silicon.

V. Defining the threshold voltage

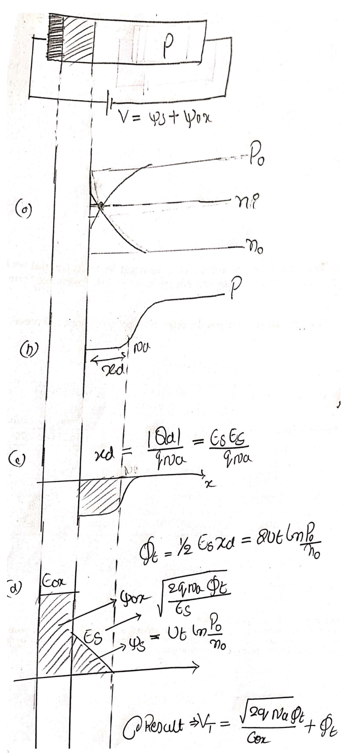

Fig. 8. Threshold voltage defining diagrams and bias Condition
a. Charge profile variation in log b. charge variation in the linear c. Depletion charge e. electric field distribution

A. *Ideal MosCap Thershold Voltage V_T*

for ideal MosCap we assumed that there is no work function difference between the metal and the silicon, so there is no band bending. As defined in the weak inversion when the gate voltage keeps raising, at some voltage the majority charges start depleting and the minority carries to pile up at the surface of the silicon and form the very weak stream of charges (channel), this small positive voltage is the threshold voltage. the applied voltage is the drop across the silicon and the oxide

$$V_T = \varphi_{ox} + \phi_t \tag{1}$$

From the Fig.9e the majority and the minority carriers in the silicon raising and minority carries start decreasing, there is a perfectly charge gradient in the silicon, from the Boltzmann charge gradient potential approximation, the drop in the silicon can be expressed and the concentration of the excessive charges in the silicon.

$$\varphi_s = V_t \ln p_0/n_0 \tag{2}$$

, from the silicon dioxide and the silicon material characteristics, the potential drop across the oxide can be estimated as

$$\varphi_{0x} = Et_{0x} = 3E_s t_{0x} \tag{3}$$

, the maximum potential drop in the silicon is,

$$1/2 E_s x_d = 2\varphi_s,\ 2\varphi_s \tag{4}$$

Due to the intrinsic band bending of the silicon in the strong inversion there is a drop in the silicon. when the silicon drop approaches maximum in the inversion, this is the surface potential ϕ_t of the silicon. The surface potential of the silicon is 2 times of the silicon drop, where

$$\phi_t = 1/2 E_s x_d = 2\varphi_s,\ x_d \tag{5}$$

, x_d is the depletion layer in the silicon from the **guass law** we can define the depletion region

$$x_d = |Q_d|/qN_a \tag{6}$$

, Q_d, is the depletion charge in the silicon and the N_a is the Doping density of the silicon.

$$Q_d = \epsilon_s E_s/qN_a,\ E_s \tag{7}$$

is the electric field in the silicon. from the depletion layer approximation and the surface potential in the silicon electric field in the silicon...

$$E_s = \sqrt{2\varphi_t q N_a/\epsilon_s} \tag{8}$$

in the equation the constant 3 is the $3 = \varepsilon_s/\varepsilon_{0x}$ from the equation [3],[8] the drop across the oxide is interpreted as

$$\varphi_{0x} = \sqrt{2qN_a\epsilon_s t_{0x}/\varepsilon_{0x}} \tag{9}$$

$$C_{0x} = \varepsilon_{0x}/t_{0x} \tag{10}$$

$$\varphi_{0x} = \sqrt{2qN_a\epsilon_s}/C_{0x} \tag{11}$$

substituting the equation [11] in the equation [1] threshold voltage for the ideal mos cap extracted

$$V_T = \sqrt{2qN_a\epsilon_s}/C_{0x} + \phi_t \tag{12}$$

VI. Charge variation model of the MosCap

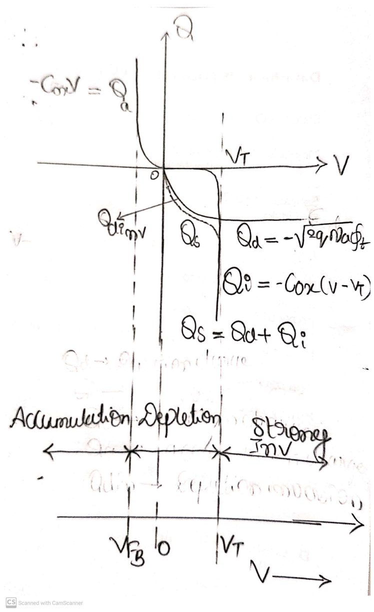

Fig. 9. Charge Profile variation in the Silicon

A. Charge variation in the Accumulation $V < 0$

In the accumulation, the majority charge carriers increase with respect to the applied negative voltage and it equals to

$$Q_a = -VC_{0x} \tag{13}$$

B. Charge variation in the Depletion $V \leq V_T, \varphi_s \leq \phi_t$

In the depletion the applied voltage less than the threshold voltage and the drop across the silicon is also less than the surface potential of the silicon this will result in the variation of both depletion charges Q_d and the Q_{dinv} inversion charges takes place at the same time. Now the threshold voltage is the summation of the drop across the silicon and the oxide

$$V = -Q_d \div C_{0x} + \varphi_s \tag{14}$$

, the inversion charges in the silicon depend on the surface potential ϕ_t and the depletion charges depends on the drop in the silicon, now the surface potential and the silicon drop is no longer equal so we can write the dependence of the inversion charge variation at depletion $Q_{dinv} = \sqrt{2qN_a\varepsilon_s\varphi_s}$, so the $\varphi_s = Q_d^2 \div 2qN_a\varepsilon_s$, from the equation.[13] the applied voltage depends on charges variation in the depletion,

$$V = -(Q_d \div C_{0x} - Q_d^2 \div 2qN_a\varepsilon_s) \tag{15}$$

C. Charge variation in the Strong Inversion $V > V_T, \varphi_s = \phi_t$

In the strong inversion, the applied voltage still depends on the drop across the oxide and the silicon potential drop approaches to the surface potential and the surface potential voltage is no longer changes because it depends on the doping levels, not on the biasing condition, so the applied remaining voltage has to drop across the oxide now the oxide drop not only depends on the inversion charge in the channel and the depletion charge. The total charge in the silicon $Q_s = (Q_{dinv} + Q_i)$, $\varphi_{ox} = -Q_s \div C_{ox}$, Q_{dinv} depletion charge in inversion,

$$V = \varphi_{ox} + \phi_t \tag{16}$$

$$V = -Q_s \div C_{ox} + \phi_t \tag{17}$$

$$V_T = -Q_{dinv} \div C_{ox} + \phi_t \tag{18}$$

,

the inversion charge is constant for the applied voltage beyond for threshold concerning the gate oxide capacitance C_{0x}

$$Q_{inv} = -(V - V_T)C_{0x} \tag{19}$$

VII. Analysis of the normalized Low Frequency CV curve

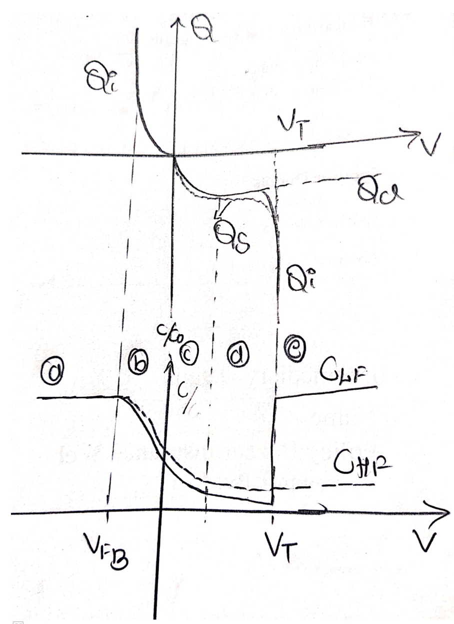

Fig. 10. Charge variation and the Capacitance variation in the Low frequency and the high frequency

We Can summarize the equation [13][15][19], the charges in the accumulation the Q_a is constant for the given applied voltage concerning the gate oxide capacitance, in the depletion layer the total silicon charges Q_s are quadratic-ally depends on the applied voltage, and in the strong inversion layer the inversion charges dominate the depletion charges so the applied voltage is no longer depends on the depletion charges in the low frequency, the behaviour of the depletion charges

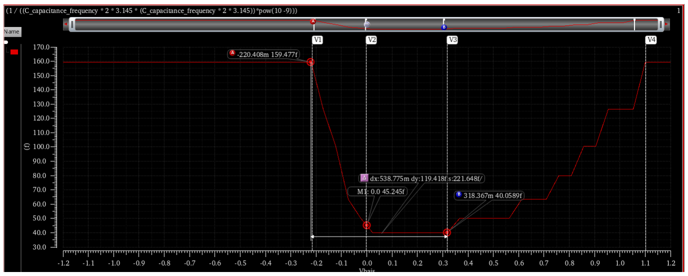

Fig. 11. Low Frequency Practical CV curve

and the inversion charges in the silicon changes in the high frequency and yet to explain and the dominating inversion charges still constant for the applied voltage for the beyond the threshold. From the charge variation profile, we can extract the small-signal capacitance of the Mos since the capacitance is the derivative of the charge for the small applied voltage.

$$C_{LF} = |\partial Q \div \partial V| \tag{20}$$

A. Introducing Non idealists in to the MosCap

From the material theory usually for constructing the MosCap the work function of the metal and silicon is no longer a zero $\Phi_{ms} \neq 0$, so there are some initial charges in the silicon to nullify the initial charges we have to apply some external voltage, so we have to consider this extra voltage. This voltage we usually call the flat band voltage because we are trying to bring the thermal equilibrium condition and make the energy bands constant, these extra voltage shifts the threshold from the ideal threshold of the MosCap. The second non-idealism is the fixed charges at the contact of the silicon dioxide and the silicon, these charges usually defined by the manufacturing process and Q_f most probably positive charges, these are the main non-idealists that can be introduced into the practical MosCap, from this non-idealities the threshold voltage, is modified as

$$V_T = \varphi_{ox} + \phi_t + V_{fb} + -Q_f/C_{ox} \tag{21}$$

B. Explanation of the typical regions in the LF MosCap CV plot

from Charge profile Fig.[10] and the non ideal analysis we can explain the realistic CV plot of the Mos Cap,

1) Practical Results of the LF CV plot:

- **Region A :** in region A the applied voltage is the beyond the flat band voltage ($V < V_{fb}$) mos is in the accumulation from the charge profile the charges (Q_a) are constant for the applied voltage and so the derivative of the applied accumulation charge and the applied voltage is constant, so the small-signal capacitance is equal to the gate oxide capacitance C_{0x}.
- **Region B :** when ($V_{fb} < V \leq 0$), the mos cap in the weak Accumulation region, the minority carriers are starting piling up and the depletion is created in the silicon this depletion layer makes the series capacitance for the gate oxide capacitance so we can see the almost a parabolic charge profile and the derivative of the charge is also a polynomial with decreasing the effective capacitance since the capacitors are in series.
- **Region C and D :** when ($0 < V \leq V_t$), the mos cap in the depletion region, the minority carriers more and more starting piling up from the region to the region C, D and the depletion further increase at the threshold voltage the minority carries and the majority carries almost all equal, then we can see a perfectly two equal capacitors are series then the capacitance, and the effective capacitance way more decrease at the threshold, we can also find the threshold of the MosCap by the CV plot.
- **Region E :** when ($V >> V_t$), in strong inversion the inversion charges are the dominant charges in the channel, so the effective capacitance is back to the normalized gate oxide capacitance, because of the negligible effect from the depletion charges, the generation and the recombination of the charges in the channel are enough to maintain the neutrality with the depletion charges.

VIII. Analysis of the normalized High Frequency CV curve

A. Practical MosCap CV curve

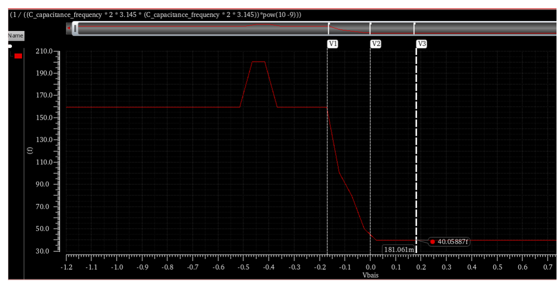

Fig. 12. High Frequency CV curve

Fig.[10] The HF CV curve of the mos is the same as the LF CV curve up to the region D, beyond the region D (beyond the threshold) if the applied signal is so fast that there is no time to generate the excess carries then, the effective capacitance is no longer back to the normalized gate capacitance. So the important question that is been yet to address is if there is no generation and recombination, then where does the channel get the inversion charges?, since there is a capacitance effect in the MosCap there are a large number of positive charges are staying, and there should be a corresponding negative charge in the channel otherwise the charge balance won't take place these excessive charges comes from the very edge of the depletion region in the silicon.

IX. Results of the LF and HF MosCap CV curve

A. Procedure and steps followed to calculate the CV characteristics of MosCap

Since the capacitor is reactive devices the characters of the capacitor cant find in the stable dc, for finding the capacitance the basic idea is the resonance behaviour of the Parallel RLC

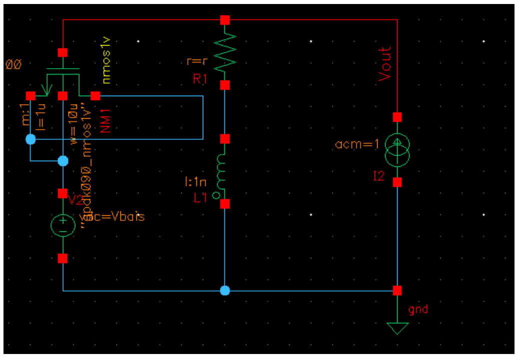

Fig. 13. Low frequency Capacitance testing Ckt

circuit, where the resonance frequency of the tank changes concerning the capacitance in the tank. At the resonance the reluctance of the inductor and the reluctance of the capacitor is equal and out of face both get cancel the input only impedance is seen into the RLC circuit is purely reactive. Fig.[13] show the RLC circuit, a small AC signal is injected to the tank and measured the voltage, at the resonance the voltage across the tank is max, by ac simulation plot output voltage across as the tank function of the frequency. A tank voltage curve can be obtained as the function of the frequency and send the ADE voltage curve to the calculator in the simulator and find the maximum input voltage corresponding resonance frequency. The mathematical function Xmax in the calculator helps to find the max output coordinator(frequency). Now the obtained frequency is a scalar quantity because it corresponding to the single-bias voltage. To obtaining the frequency curve for the applied bias voltage of the MosCap, add the bias voltage of the cap into the parametric analysis, run the parameter analysis, this simulation frequency curve for the applied voltage. obtained frequency curve is not direct capacitance of the mos, get the effective capacitance curve send the frequency curve to the calculator and with know inductance and the frequency curve $C = 1 \div ((2pi * f0_{wave})^2 * L)$, plot the capacitance curve for the applied voltage.

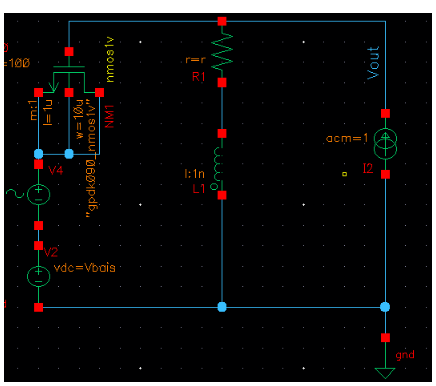

Fig. 14. High frequency Capacitance testing Ckt

for the high frequency cv curve add a sinusoidal ac signal series with the dc bias voltage of the mos Fig.[14].

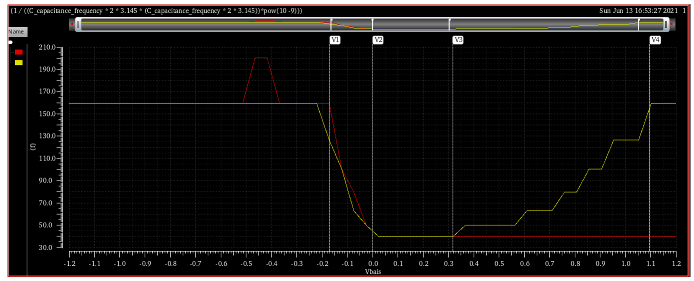

Fig. 15. Low Frequency and High Frequency MosCap CV curve

Fig.[13] shows the practical MosCap CV curves, the curve is not smooth, but we can still find the Normalized capacitance. but the main issue with the abrupt stepping curve we are unable to locate the threshold voltage of the mas cap, then what could be the solution ?, we can take the derivative of the LF CV curve for the smoothness and from the smooth CV curve threshold voltage V_T can be located easily.

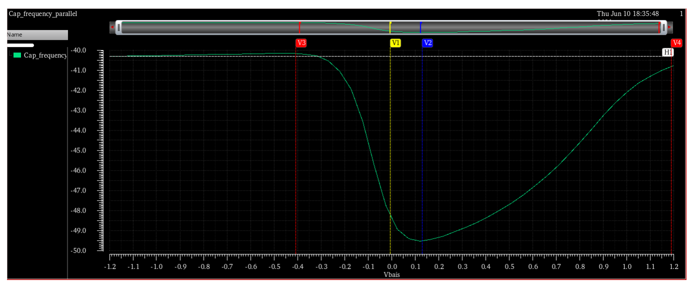

Fig. 16. derivative of the LF MosCap CV curve

In the Fig.[16] the threshold voltage where the Normalized capacitance is at minimum, from this particular curve the threshold voltage of the MosCap is 180mV.

X. Application of the MosCap

A. MosCap ring Oscillator

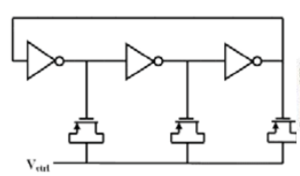

Fig. 17. Typical three stage MosCap Ring oscillator

VCO's are the most demanding section in the RF system design, the key feature of the VCO is the tuneability of the oscillator for the desired frequency. This report contains the VCO ring oscillator as the application of the mos cap, Fig.[17] shows the three-stage ring oscillator with tun able mocap.

Fig.[18] shows the Gain of the VCO $K_{vco} = \partial f_0 \div \partial V_{ctrl}$,indeed the Moscap works fine, in fact we see the

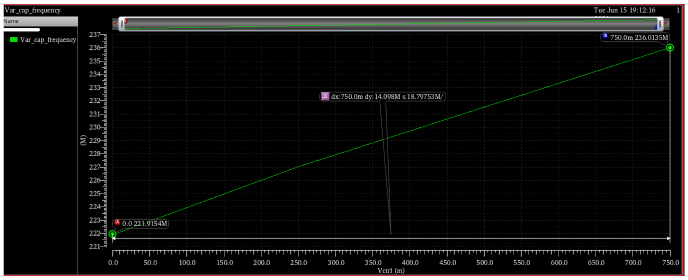

Fig. 18. K_{vco} of the MosCap ring oscillator

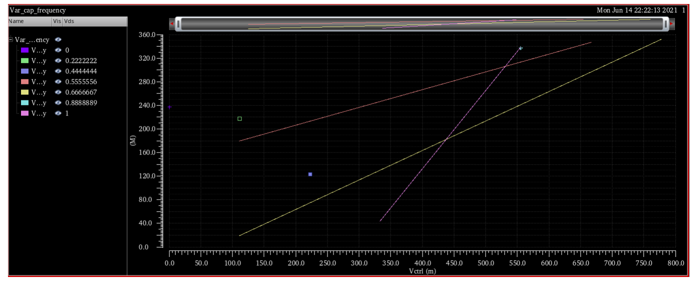

Fig. 21. Variation of the VCO slope and the tune able frequency range for MosCap control voltage

practical application Fig .[18]we can see that the allows a tun-able range of the 18MHz, but varying the K_{vco} is also pretty much demanding from the two-terminal MosCap we can't achieve the variables K_{vco}. To obtain variable VCO gain slope we can introduce one more terminal in the mocap Fig .[19] where drain and source are sharted and applied fixed voltage, this configuration allows to create some extra charge apart from the main control voltage at the bulk.

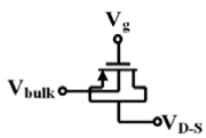

Fig. 19. Three terminal MosCap

A complete circuit of the three terminal MosCap VCO ring oscillator is reported in Fig .[20], where the V_{ds} sets the slope of the VCO gain and the V_{ctrl} is the tune able voltage.

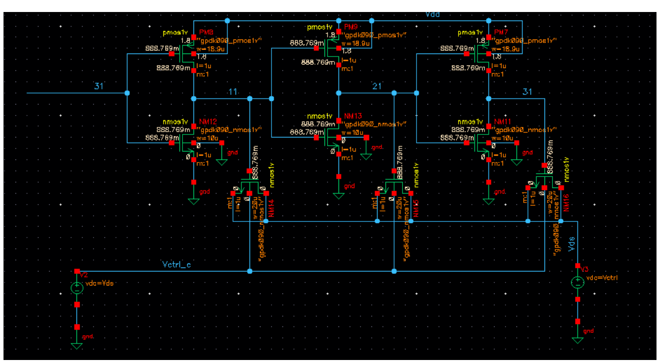

Fig. 20. Complete three terminal MosCap VCO ring oscillator

Fig .[21] show the gain the of the VCO K_{vco} for variable Vds of the MosCap,this solution is clearly give more flexibility in terms of the tune able range and the response of the VCO.

CONCLUSION

This report is mainly prepared for academic purpose and student study purpose. The report yet to describe the detailed analysis of the HF CV curve, from my knowledge of the course and study, I am unable to explain the hump in the HF CV curve near the flat band voltage and some second-order effects on the MosCap.

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