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ABSTRACT

CMOS technology has revolutionized the electronics industry, enabling the development of increasingly complex and powerful integrated circuits. This project focuses on investigating the key performance parameters of CMOS devices, including delay, power consumption, and area. We explore the impact of various factors on these parameters, such as power supply voltage, device dimensions (channel width and length), gate oxide thickness, and threshold voltage. Through literature review and simulation-based analysis using Cadence Virtuoso, we aim to gain a deeper understanding of the trade-offs involved in optimizing CMOS circuit performance. The project will analyze the sensitivity of CMOS delay to device parameters, focusing on how variations in these parameters affect the rise and fall times of the output signals. By investigating these critical aspects, this project contributes to a better understanding of CMOS technology and its limitations, paving the way for future advancements in integrated circuit design and enabling the development of even more efficient and sophisticated electronic systems.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

CONCEPTION OF THE PROJECT

1.1 Introduction:

Complementary Metal-Oxide-Semiconductor (CMOS) technology has emerged as the dominant technology in modern integrated circuits, driving advancements in various fields such as computing, communication, and consumer electronics. The inherent advantages of CMOS, such as low power consumption, high noise immunity, and high packing density, have enabled the continuous miniaturization and performance enhancement of integrated circuits. CMOS circuits operate by utilizing both p-type and n-type transistors in a complementary fashion, resulting in minimal power dissipation in both static and dynamic states. This energy efficiency is crucial for portable devices and large-scale systems, where power consumption is a critical concern. Furthermore, the complementary nature of the transistors provides excellent noise immunity, ensuring reliable circuit operation even in the presence of external disturbances. The ability to integrate a high number of transistors within a small area has led to the development of increasingly complex and powerful systems on a single chip.

The performance of CMOS circuits is evaluated based on several key parameters, including speed, power consumption, area, and reliability. Speed, typically measured by parameters such as delay, rise/fall time, and bandwidth, determines how quickly the circuit can process information. Power consumption is a critical factor, impacting both the energy efficiency and operating temperature of the circuit. Area, the amount of silicon area occupied by the circuit on the chip, directly influences the cost and integration density. Reliability ensures that the circuit functions correctly over time and under various environmental conditions.

This project aims to delve into the intricacies of these performance parameters, investigating the factors that influence them and analyzing the trade-offs involved. By studying the impact of transistor dimensions, supply voltage, temperature, and process variations on circuit performance, we can gain valuable insights into optimizing circuit design for specific applications. This includes exploring techniques for minimizing power consumption while maintaining high speed, maximizing area efficiency, and enhancing reliability.

1.2 Motivation

- Meeting the ever-growing demands of modern electronics: Modern applications require devices that are not only powerful but also energy-efficient, compact, and reliable. CMOS technology, with its inherent advantages, plays a crucial role in enabling these advancements.
- Driving innovation across various fields: CMOS performance directly impacts the capabilities of devices in telecommunications, computing, and portable electronics, driving advancements in these and other sectors.
- Addressing the challenges of miniaturization and scaling: As CMOS technology scales down, new challenges arise. Studying performance at the nanoscale level helps researchers identify and address these challenges to ensure the continued progress of Moore's Law.
- Enabling sustainable and energy-efficient solutions: With increasing concerns about energy consumption, optimizing CMOS performance for low power consumption is crucial for developing environmentally friendly electronics.

1.3 Background

A CMOS (Complementary Metal-Oxide-Semiconductor) device is a type of field-effect transistor that forms the foundation of modern integrated circuits. It utilizes both p-type (PMOS) and n-type (NMOS) transistors in a complementary configuration, leading to low power consumption and high noise immunity.

The performance of CMOS devices is evaluated based on several critical parameters, including:

- Delay: The time it takes for the output of a logic gate to respond to an input change. Influenced by factors like power supply voltage, device dimensions, and threshold voltage.
- Power Consumption: A crucial factor, especially for portable devices. It includes both static and dynamic power dissipation.
- Area: The amount of silicon area occupied by the device on the chip, directly impacting cost and integration density.
- Reliability: The ability of the device to function correctly over time and under various environmental conditions.

By carefully considering and optimizing these factors, designers can create efficient and high-performance CMOS circuits.

1.4 Objectives

- To perform detailed literature survey on various CMOS performance factors: This objective emphasizes the importance of thorough research and understanding of existing knowledge in the field of CMOS technology. It involves exploring and analyzing various published works, research papers, and technical documents related to CMOS performance parameters, their characteristics, and influencing factors.

- To investigate sensitivity of CMOS delay to device parameters: This objective focuses on a specific aspect of CMOS performance – delay. It aims to understand how variations in device parameters (such as transistor dimensions, supply voltage, temperature, etc.) affect the delay of CMOS circuits. This analysis will provide insights into the criticality of device parameter control for achieving desired circuit performance.

1.5 Problem Statement:

- To perform detailed study, analysis on various CMOS performance factors in VLSI technology

- To perform performance related simulations using CADENCE virtuoso (90nm).

1.6 Areas of Application:

- Microprocessors and Microcontrollers: CMOS is the cornerstone of modern microprocessors and microcontrollers used in computers, smartphones, and embedded systems.

- Memory Devices: CMOS technology is used in various memory devices, including static RAM (SRAM), dynamic RAM (DRAM), and flash memory.

- Communication Systems: CMOS devices are essential components in communication systems, such as wireless transmitters and receivers, modems, and baseband processors.

- Analog Circuits: CMOS technology is also used to implement various analog circuits, such as operational amplifiers, data converters, and filters.

- Power Management Integrated Circuits (PMICs): CMOS is used in PMICs to regulate and manage power in electronic systems, improving efficiency and battery life.

- Sensors and Actuators: CMOS technology is being increasingly used to integrate sensors and actuators on a single chip, enabling the development of smart devices and systems.

1.7 Literature Survey:

SI No.	Authors	Year Of Publication	Title	Techniques Employed
1.	Yuan Taur and Tak H. Ning	2022	Fundamentals of modern VLSI Devices	Scaling techniques
2.	Sarthak Talwara , B. Mohapatrab and Mohammad Rashid Ansari	2020	Performance Analysis of CMOS Technology	Reduction of Parasitic
3.	Zitong Han	2020	The power-delay product and its implication to CMOS Inverter	Gate sizing and transistor sizing
4.	Vikas Singhai, Saima Ayyub, Paresh Rawat	2016	Comparison of Leakage Power Reduction Techniques in 65nm Technologies	Leakage Power Reduction Techniques

CHAPTER-2

DESIGN OF PROJECT

2.1 Design Methodology:

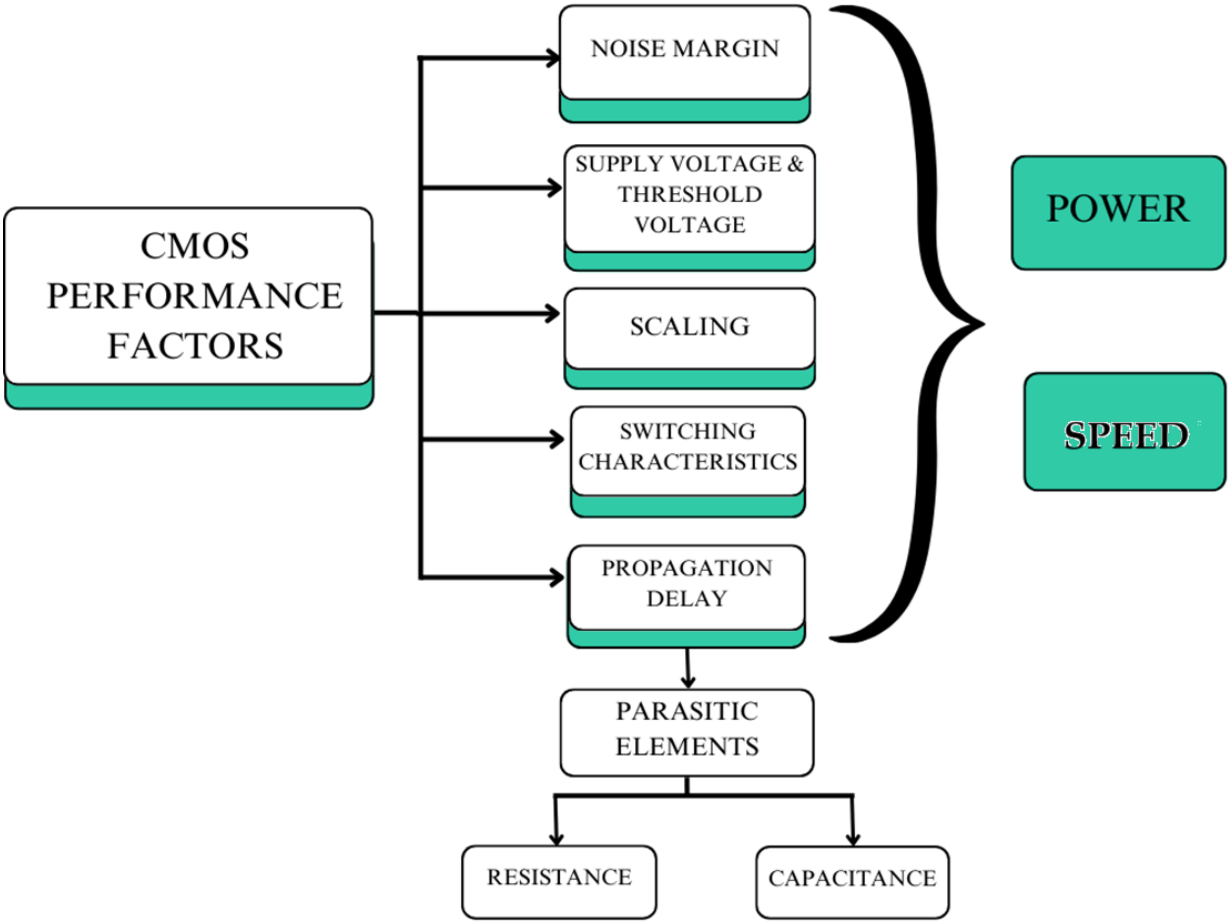

Fig 2.1: CMOS Performance factors

Figure 2.1 describes the sensitivity of CMOS performance factors to delay.

2.2 Preliminary Studies:

1. Noise Margin

Noise margin is the tolerance level for unwanted voltage (noise) that can be present on an input signal without causing errors in the output.

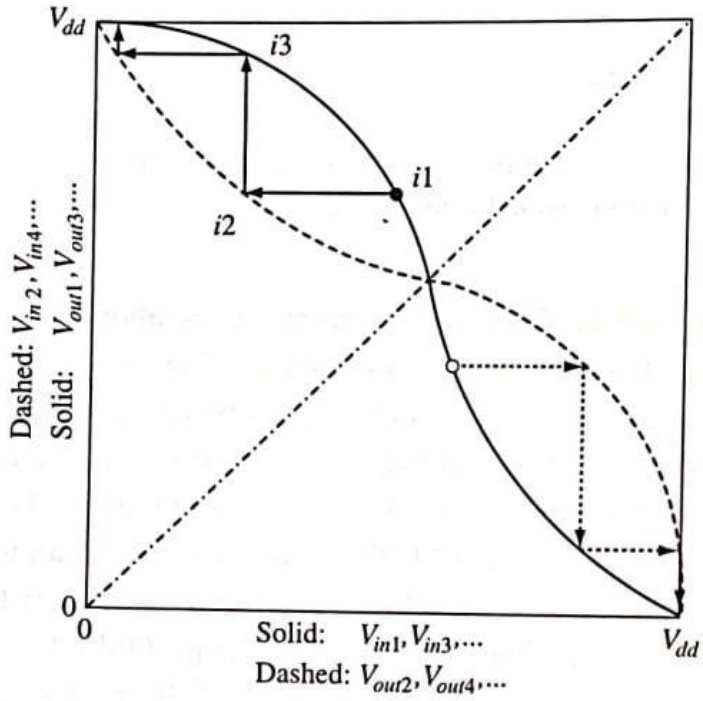

Fig 2.2: Noise margin analysis of inverter

Figure 2.2 describes the solid transfer curve is for odd numbered inverter stages. The flipped, dashed transfer curve is for even numbered stages.

Noise margin for a given transfer curve is measured by the size of the maximum square that can fit between itself and its complementary curve.

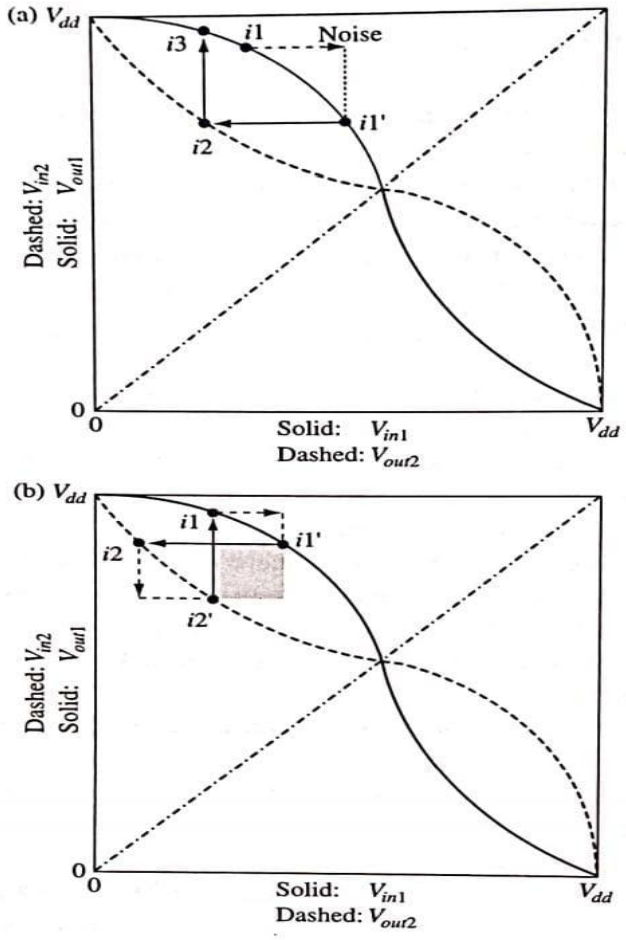

Fig 2.3: Node voltage trajectory

Figure 2.3 a) describes the node voltage trajectory with noise added to the input to inverter. b) Node voltage trajectory with positive noise at inverter #1 and negative noise at inverter #2.

2. Switching Characteristics:

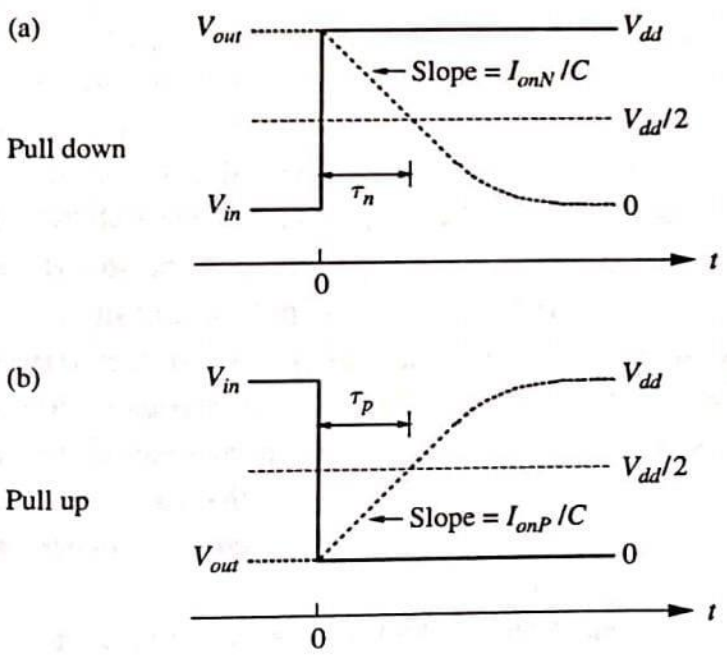

Fig 2.4: Waveforms of output node voltage of CMOS inverter

Figure 2.4 describes waveforms of the output node voltage (dotted) of a CMOS inverter. (a) Pull-down transition after an abrupt rise of input voltage (solid). (b) Pull-up transition after an abrupt fall of input voltage (solid).

- Overview of CMOS Inverter Switching: Describes the basic switching characteristics of a CMOS inverter, especially when the gate voltage undergoes an abrupt or infinitely sharp transition.
- Switching Transition: Example: In an inverter, when Vin transitions from 0 to Vdd. Before the transition, the nMOSFET is off, and the pMOSFET is on. After the transition, the nMOSFET is on, and the pMOSFET is off.
- Pull-Down Switching Characteristics: The switching behaviour is defined by the differential equation:

  (C_+C+)dVout/dt=−IN(Vin=Vdd)

- Definition of nMOSFET Pull-Down Delay (τn): Defined as the time it takes for the output node voltage to reach Vdd/2.
- Definition of pMOSFET Pull-Up Delay (τp): Defined as the time for the output voltage to rise.

3. Propagation delay of CMOS inverter:

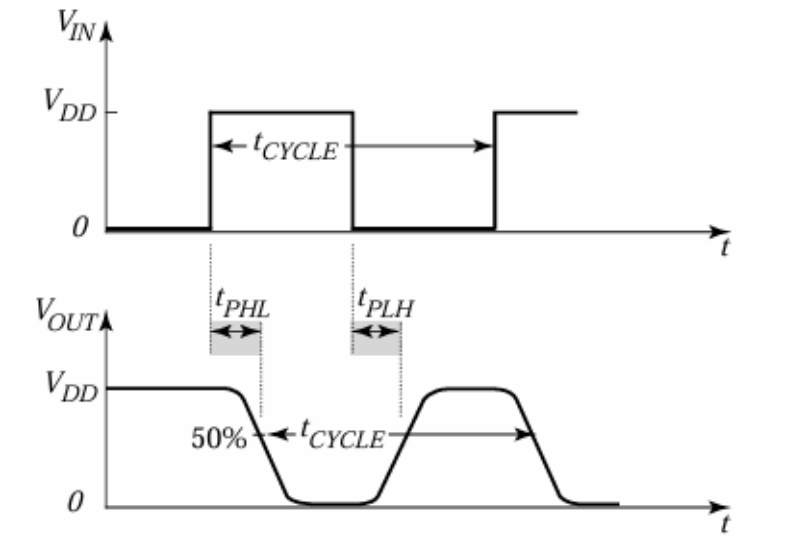

Fig 2.5: Propagation delay

- Inverter propagation delay: Time delay between input and output signals; figure of merit of logic speed. Typical propagation delays: < 100 ps.
- Average propagation delay**:** $t_p = (T_{PHL}+T_{LHP})/2$.

Where, T_{PHL}= propagation delay high to low and T_{PLH}= propagation delay low to high

- Propagation delay and Power trade-off**:** V_{DD} increases⇒ t_p decreases

Reason**:** V_{DD} increases as a result, the overdrive voltage V_{GS}-V_{TH} is also increased which increases the current I_D

Trade-off**:** As V_{dd} increases more power is consumed.

4. Parasitic Elements:

Parasitic elements in CMOS (Complementary Metal-Oxide-Semiconductor) circuits refer to unintended components, such as capacitances, resistances, and sometimes inductances, that arise from the physical layout and materials used in semiconductor devices. These elements can affect the performance, power consumption, and reliability of CMOS circuits, especially as devices are scaled down in size. Common parasitic elements in CMOS:

i) Source-Drain Resistance

ii) Gate Resistance

iii) Junction Capacitance

iv) Overlap Capacitance

v) Interconnect R and C

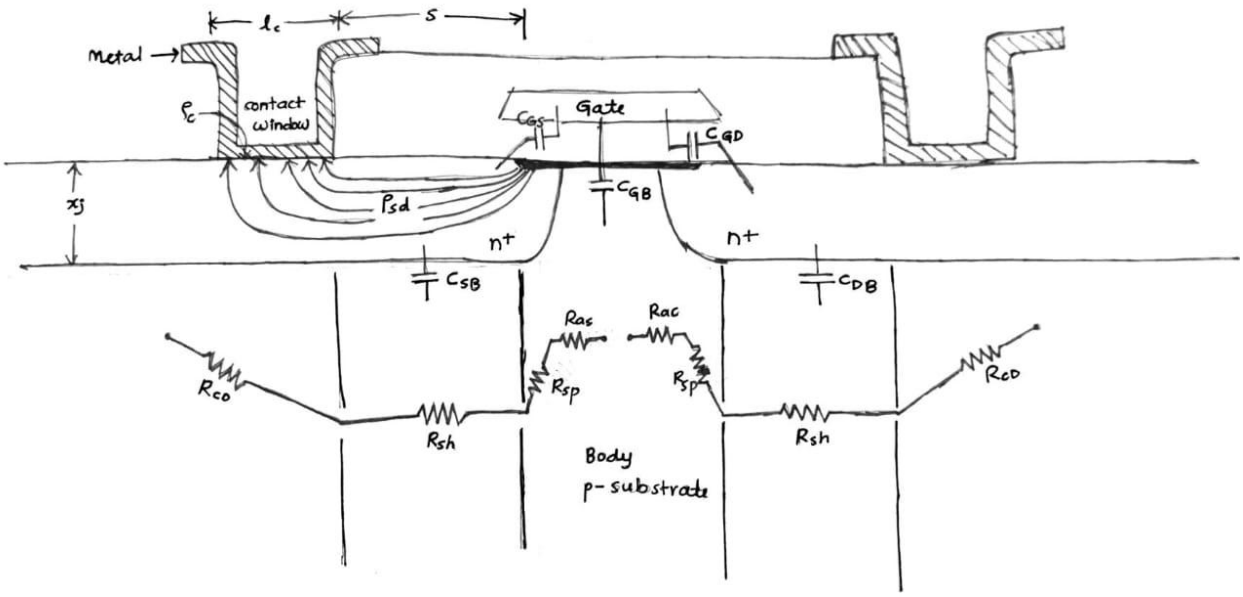

Fig 2.6: Parasitic elements of CMOS circuits.

CMOS LOGIC CIRCUITS	POWER	DELAY
INVERTER	46 nW	16.33 ps
NAND	40.35 nW	26.71 ps
NOR	52.7 nW	31.718 ps

Table 2.1: Power and Delay of CMOS logic circuits.

Table 2.1 describes the preliminary results obtained by performing power and delay analysis of various CMOS logic circuits such as NOR, NAND, and INVERTER

2.3 CMOS Performance Factors

1. Power Supply Voltage (V_{dd}):

In CMOS circuits, the power supply voltage (V_{dd}) is the DC voltage level that provides the necessary energy for the transistors to operate. It sets the maximum voltage swing available for signal transitions.

The relationship between V_{dd} and delay in CMOS circuits is complex and multifaceted. Here are the key factors of how V_{dd} affects delay:

- Subthreshold Conduction: At low V_{dd} values, subthreshold conduction increases. Subthreshold conduction is the leakage current that flows through the MOSFET even when the gate-to-source voltage (V_{gs}) is below the threshold voltage (V_{th}). This leakage current increases delay as it slows down the charging and discharging of the output node.

- Carrier Velocity Saturation: As V_{dd} increases, the velocity of charge carriers (electrons and holes) in the channel of the MOSFET also increases. However, the carrier velocity eventually saturates due to various physical limitations. This saturation effect limits the speed improvement that can be achieved by simply increasing V_{dd}.

- Short-Channel Effects: At higher V_{dd} values, short-channel effects become more pronounced in scaled-down devices. These effects, such as channel length modulation and velocity saturation, can lead to increased leakage current and reduced transistor current drive, which can negatively impact delay.

- Power Consumption: Increasing V_{dd} generally increases the dynamic power consumption of the circuit. Dynamic power is primarily due to the charging and discharging of the load capacitance. Higher V_{dd} leads to larger voltage swings and thus higher charging/discharging currents, resulting in increased power consumption.

2. Threshold Voltage (Vth)

The threshold voltage (Vth) of a MOSFET (Metal-Oxide-Semiconductor Field-Effect Transistor) is the minimum gate-to-source voltage (V_{gs}) required to create a conducting channel between the source and drain terminals. In simpler terms, it's the voltage needed to turn the transistor "on."

While there's no single, universal formula for Vth due to its dependence on various factors, a simplified expression can be given as:

$V_{th} = V_{fb} + 2*\varphi_f + \gamma*(sqrt(2*\varphi_f + V_{sb}) - sqrt(2*\varphi_f))$

Where:

V_{fb}: Flat-band voltage (depends on work function difference between gate and substrate)

φf: Fermi potential of the semiconductor

γ: Body effect coefficient

V_{sb}: Source-to-bulk voltage

3. Channel Width

The channel width (W) of a MOSFET is the physical dimension of the conducting channel between the source and drain terminals. It's essentially the width of the active region where charge carriers flow.

Impact on Delay:

The channel width significantly influences the delay characteristics of CMOS circuits:

Current Drive:

i) Wider Channel:

- Allows for higher current flow through the transistor.
- Faster charging and discharging of the output node.
- Reduced delay.

ii) Narrower Channel:

- Limits current flow, leading to slower charging and discharging.
- Increased delay.

Resistance:

Wider channels have lower resistance, which reduces the voltage drop across the transistor and improves its current driving capability.

This contributes to faster switching speeds and lower delay. The relationship between channel width and drain current (Id) can be approximated by:

$$Id \propto W$$

This indicates that the drain current is directly proportional to the channel width, assuming other parameters remain constant.

Optimizing Channel Width:

- Trade-offs: Increasing channel width generally reduces delay but also increases the area occupied by the transistor and can lead to increased power consumption.
- Design Considerations: Careful consideration of channel width is crucial in circuit design to achieve the desired balance between speed, power, and area.

4. Channel Length

The channel length (L) of a MOSFET is the physical distance between the source and drain terminals of the transistor. It's a crucial parameter that significantly influences the device's electrical characteristics.

Impact on Delay:

Short-Channel Effects:

Reduced Control: As channel length decreases, it becomes increasingly difficult to control the electric field within the channel. This leads to various short-channel effects like:

Velocity Saturation: Carrier velocity saturates at high electric fields, limiting the current drive and increasing delay.

Channel Length Modulation: The effective channel length decreases with increasing drain voltage, leading to increased leakage current and reduced output resistance.

Subthreshold Leakage:

Shorter channel lengths can increase subthreshold leakage current, which is the current flowing through the transistor even when it's theoretically "off. “This leakage current can impact delay and power consumption.

Performance vs. Scalability:

Reducing channel length is a key driver of device scaling and miniaturization in the semiconductor industry. However, as channel lengths continue to shrink, managing short-channel effects and maintaining device performance becomes increasingly challenging.

Optimizing Channel Length:

- Trade-offs: Reducing channel length generally improves speed but exacerbates short-channel effects.
- Advanced Techniques: Techniques like strain engineering, high-k dielectrics, and novel device architectures are employed to mitigate short-channel effects and maintain performance as channel lengths continue to shrink.

5. Gate Oxide Thickness

The gate oxide is a thin insulating layer of silicon dioxide (SiO_2) that separates the gate electrode from the semiconductor channel in a MOSFET. Its thickness plays a crucial role in determining the transistor's electrical characteristics.

Impact on Delay:

Control Over Channel:

a. Thinner Oxide: Allows for better electrostatic control over the channel. Stronger electric field can be induced in the channel with a given gate voltage. This leads to higher current drive and faster switching speeds.

b. Thicker Oxide: Reduces the control over the channel. Weaker electric field is induced for a given gate voltage. Results in lower current drive and slower switching speeds.

Subthreshold Leakage:

Thinner oxides can increase subthreshold leakage current due to higher tunnelling probability of carriers through the oxide.

Reliability Concerns:

Extremely thin oxides can lead to reliability issues like gate leakage and dielectric breakdown.

Optimizing Gate Oxide Thickness:

- Trade-offs: Reducing gate oxide thickness generally improves speed but increases the risk of reliability issues.
- High-k Dielectrics: To address these challenges, high-k dielectrics (materials with higher dielectric constants than SiO_2) are used as replacements for gate oxide.

CHAPTER-3

IMPLEMENTATION OF PROJECT

3.1 Tools/Technologies used:

Cadence Virtuoso (90nm):

- Virtuoso Schematic Editor:
  Used to design and capture CMOS circuit schematics. It allows for hierarchical design and provides an intuitive environment for creating and modifying circuit diagrams.

- Virtuoso ADE (Analog Design Environment) :
  This tool facilitates simulation setup and analysis. It supports various simulation types like DC, AC, transient, and parametric sweeps, enabling comprehensive performance evaluation of CMOS circuits.

- Spectre Circuit Simulator:
  A SPICE-level simulator used for accurate analog and mixed-signal circuit simulation. Spectre helps analyze transistor-level behavior, power, delay, and noise, crucial for verifying CMOS designs at 90nm.

- Virtuoso Layout Editor:
  Used for physical design and layout of circuits. It allows designers to place and route components according to the design rules of the 90nm process node, ensuring manufacturability and performance.

- Virtuoso Extraction and Verification (Assura/PEX):
  This tool performs parasitic extraction (PEX) and Layout Versus Schematic (LVS) checks. It ensures that the final layout accurately represents the schematic and accounts for parasitic effects that impact performance.

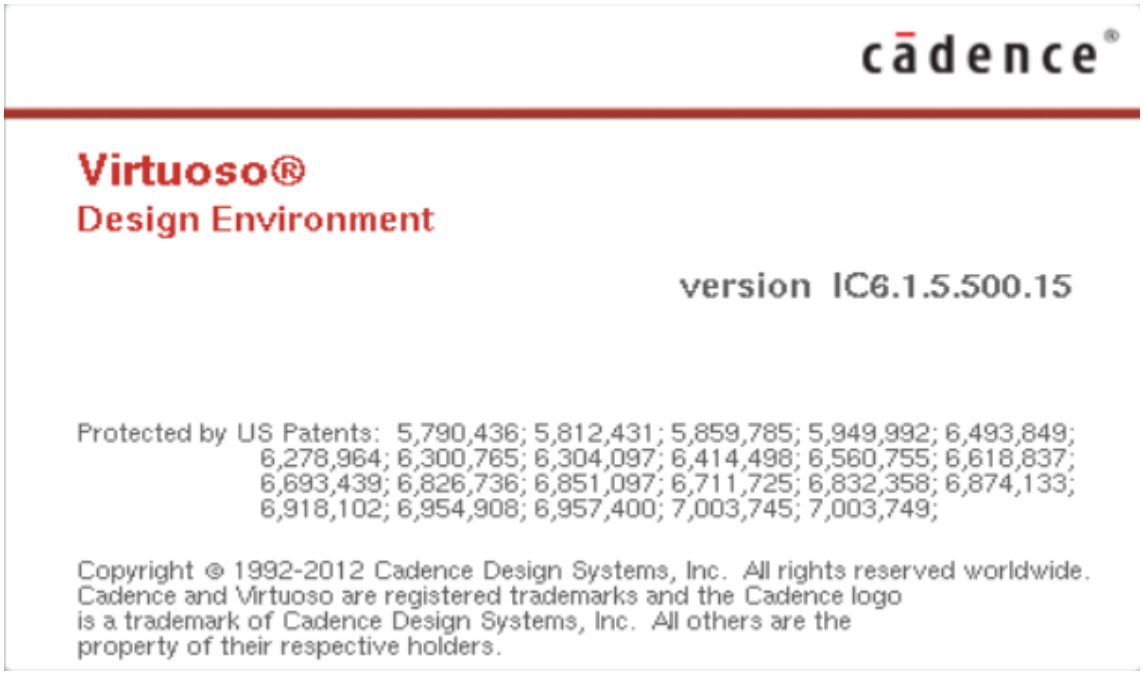

Fig 3.1: Cadence Virtuoso Design Environment

3.2 Sensitivity of CMOS delay to device parameters

1. Capacitance:

The total delay of a circuit is influenced by the time it takes to charge or discharge the load capacitance (CL) through the driving transistor. The delay can be separated into rise time (charging) and fall time (discharging).

Capacitance	0.1pF	0.3pF	0.5pF	0.8pF	1pF	2pF
Delay	1.182ns	3.378ns	5.568ns	8.77ns	10.838ns	18.75ns

Table 3.1: Capacitance Vs Delay

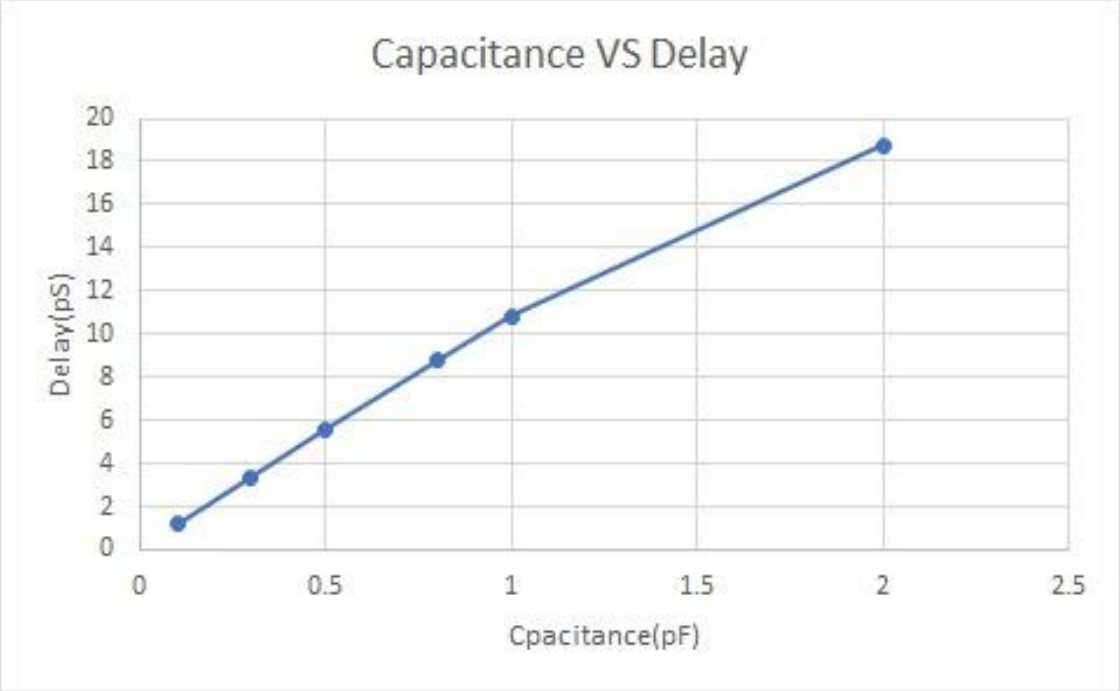

Fig 3.2: Plot of Capacitance Vs Delay

Inference:

An increase in load capacitance increases the delay in a CMOS inverter, as it takes more time to charge and discharge the capacitance. Larger load capacitance results in slower switching and higher propagation delay.

2.Threshold Voltage:

The threshold voltage (VT) is the minimum voltage required at the gate of a transistor (e.g., MOSFET) to create a conducting path between the source and drain terminals. Beyond this voltage, the transistor switches from the OFF state to the ON state.

Threshold Voltage	0.45V	0.40V	0.25V	0.125V	0.09V
Delay	82.46ps	79.52ps	50.67ps	27.33ps	14.99ps

Table 3.2: Threshold voltage Vs Delay

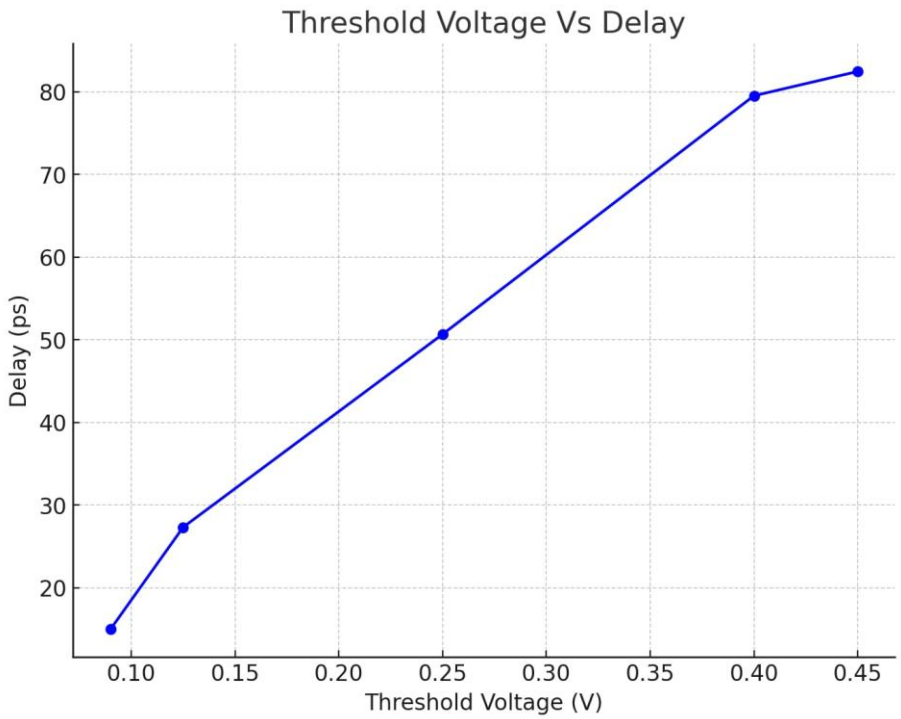

Fig 3.3: Plot of Threshold Voltage Vs Delay

Inference:

A decrease in threshold voltage lowers the required voltage for the transistor to turn on, increases the current that can flow through it, and reduces the time needed to charge discharge the capacitances associated with switching. As a result, delay decreases.

3.Power Supply Voltage:

The power supply voltage is the external voltage provided to a circuit or device to power its operation.

Power Supply Voltage	0.45V	0.7V	0.9V	1.2V	1.5V	1.8V
Delay	25.17ns	0.0953ns	0.0488ns	0.0356ns	0.0292ns	0.025ns

Table 3.3: Power Supply voltage Vs Delay

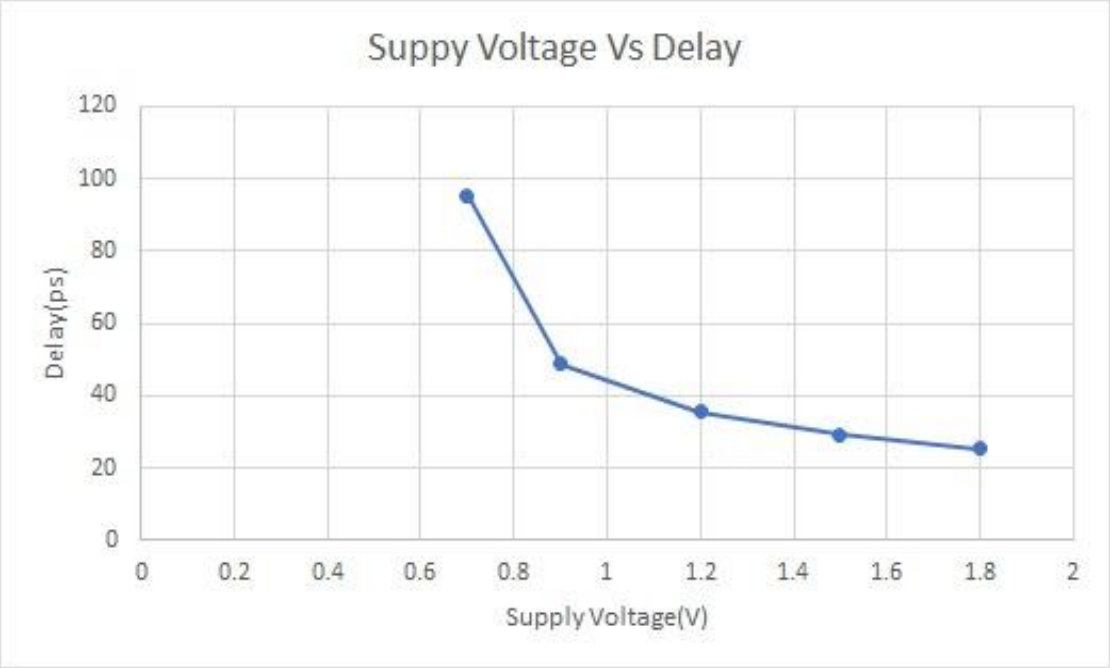

Fig 3.4: Plot of Supply Voltage Vs Delay

Inference:

An increase in delay occurs when the supply voltage (VDD) is reduced, as the transistors switch slower, resulting in longer rise and fall times. This increases the overall propagation delay of the CMOS inverter.

4.Channel Width:

The channel width refers to the width of the conductive channel in a MOSFET (Metal-Oxide-Semiconductor Field-Effect Transistor) that connects the source and drain terminals. This channel allows the flow of charge carriers (electrons or holes) when the transistor is turned on.

a) Width of PMOS =120nm (fixed):

Width of NMOS	120nm	180nm	240nm	300nm	450nm	600nm
Delay	54.01ps	56.24ps	57.73ps	59.74ps	63.98ps	67.045ps

Table 3.4: Channel Width of NMOS Vs Delay

b) Width of NMOS =120nm (fixed):

Width of PMOS	120nm	180nm	240nm	300nm	450nm	600nm
Delay	54.01ps	49.8ps	46.84ps	44.905ps	41.345ps	38.955ps

Table 3.5: Channel Width of PMOS Vs Delay

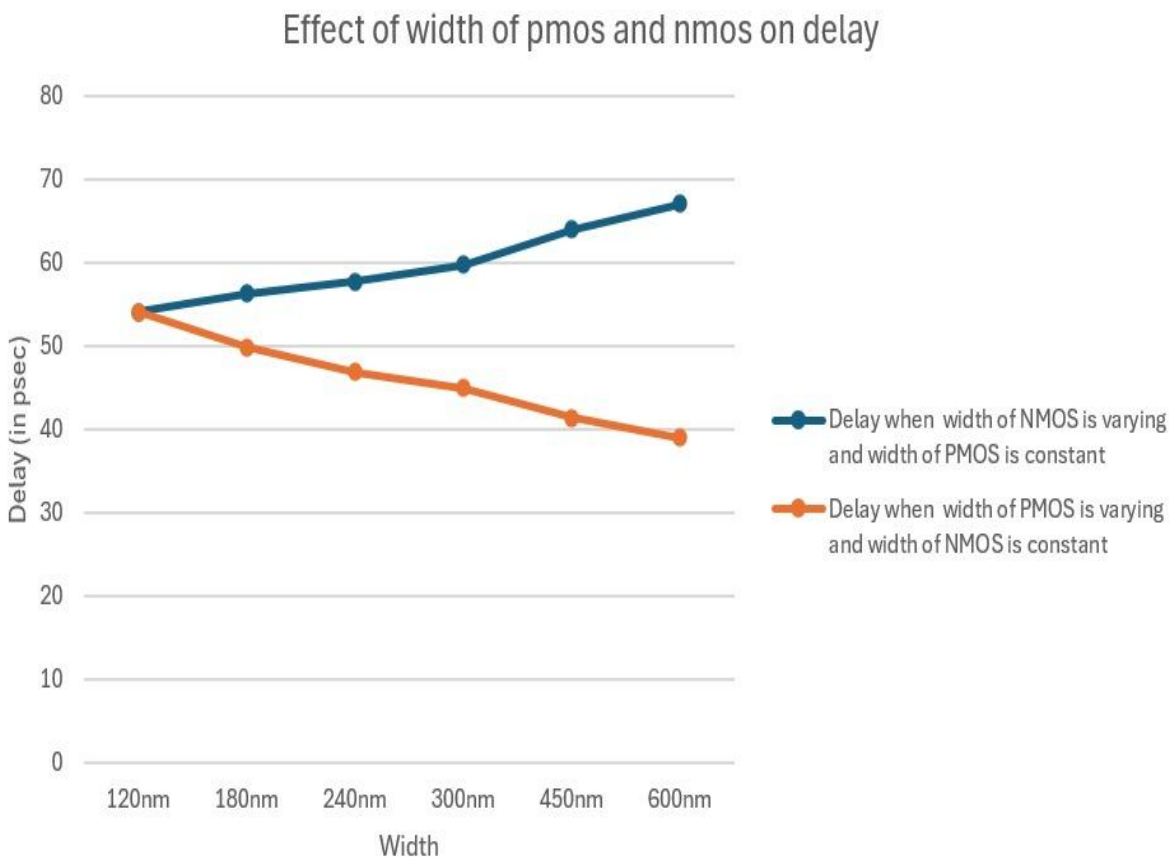

Fig 3.5: Plot of Channel width of PMOS and NMOS Vs Delay

Inference:

Increasing NMOS width increases delay due to secondary effects like leakage current, short-channel effects, or insufficient improvement in current drive. Increasing PMOS width decreases delay as it compensates for the PMOS's lower mobility, improving current drive and speeding up switching.

5.Channel length:

The channel length (L) in a MOSFET (Metal-Oxide-Semiconductor Field-Effect Transistor) refers to the distance between the source and drain terminals, where the current flows through the channel created in the semiconductor material between these two terminals.

a) Length of PMOS =100nm (fixed):

Length of NMOS	100nm	150nm	200nm	250nm	300nm	500nm
Delay	54.01ps	50.62ps	48.62ps	47.4ps	46.53ps	44.92ps

Table 3.6: Channel length of PMOS Vs Delay

b) Length of NMOS =100nm (fixed):

Length of PMOS	100nm	150nm	200nm	250nm	300nm	500nm
Delay	54.015ps	59.925ps	62.345ps	66.69ps	70.47ps	90.195ps

Table 3.7: Channel length of NMOS Vs Delay

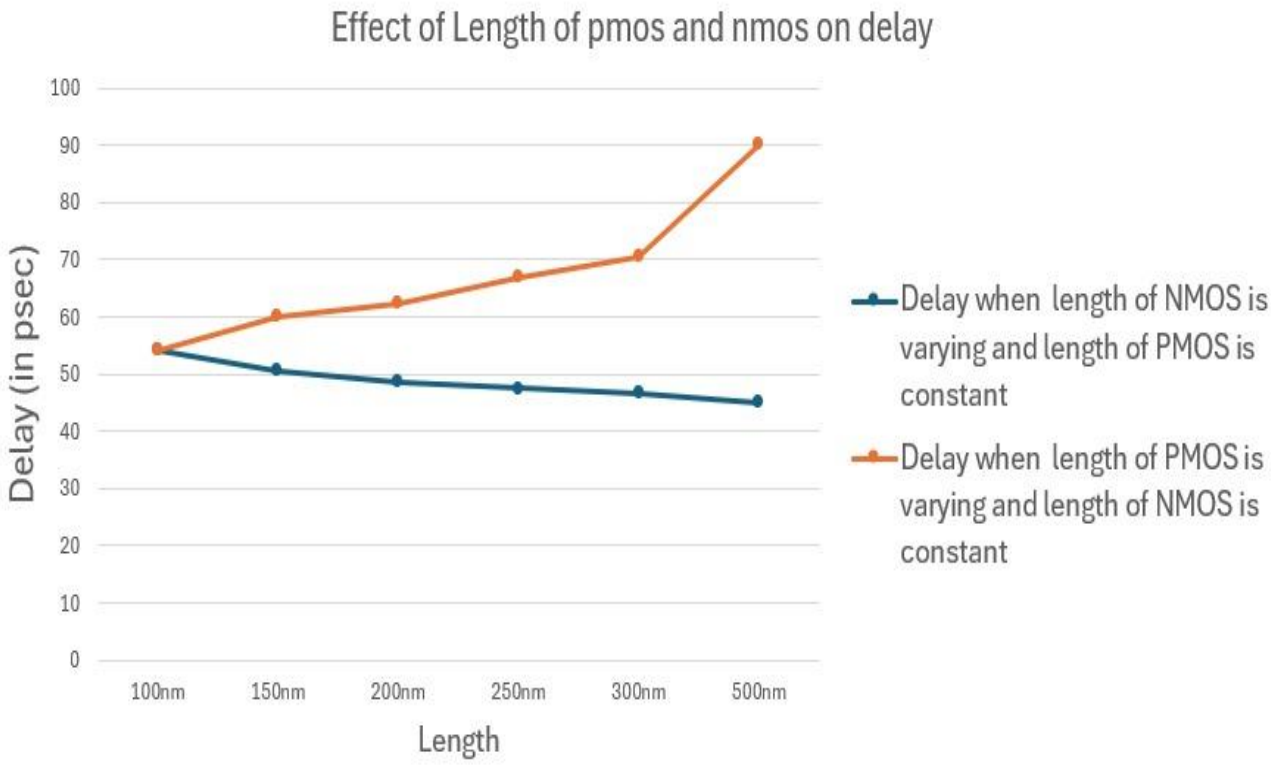

Fig 3.6: Plot of Channel Length of PMOS and NMOS Vs Delay

Inference:

The lower mobility of holes in PMOS transistors explains why delay increases significantly as the PMOS length increases, while NMOS devices exhibit a relatively stable delay.

6.Gate oxide Thickness:

Gate oxide thickness refers to the thickness of the insulating layer of oxide that separates the gate electrode from the semiconductor channel in a Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET). This layer plays a critical role in the performance of the transistor, as it controls the flow of current between the source and drain terminals by influencing the gate's ability to control the channel.

Gate oxide	2.0nm	2.5nm	3.0nm	3.5nm	4.0nm	4.5nm
Delay	20.34ps	22.89ps	25.54ps	28.23ps	31.83ps	34.61ps

Table 3.8: Gate oxide thickness Vs Delay

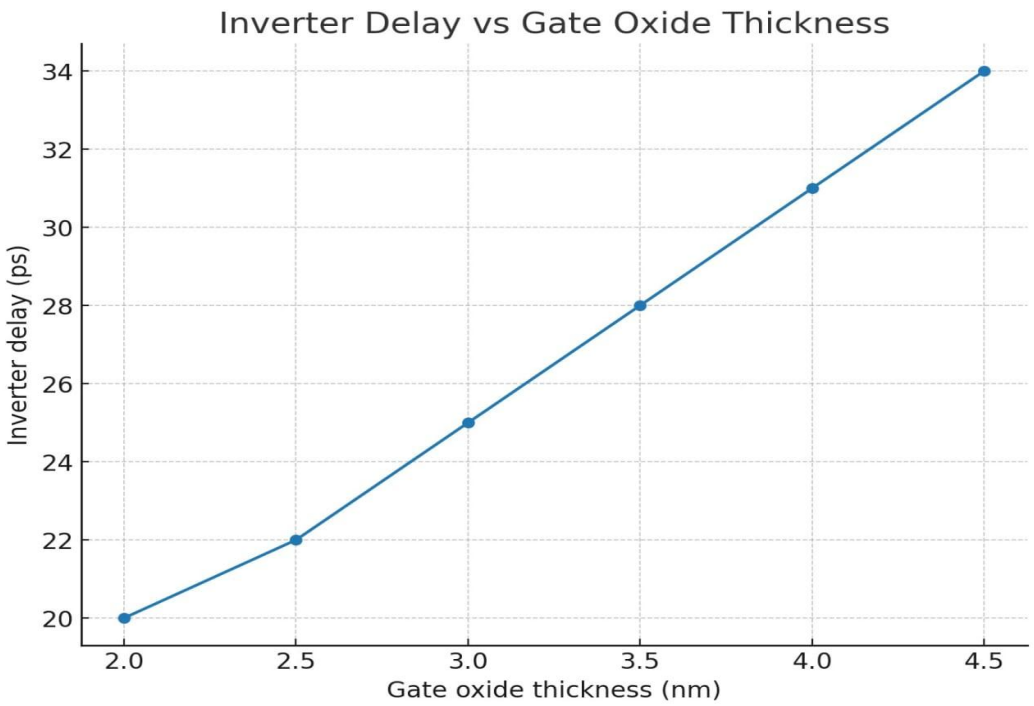

Fig 3.7: Plot of Gate oxide thickness Vs Delay

Inference:

Thinner oxide leads to a higher gate capacitance. Higher gate capacitance increases the charging/discharging time, resulting in greater propagation delay, reducing overall circuit speed and performance.

CHAPTER-4

SUMMARY AND OVERALL INFERENCE OF THE PROJECT

4.1 Results:

- NMOS and PMOS Characterization: V_{ds} vs I_{ds} and V_{gs} vs Ids curves for both NMOS and PMOS transistors were analyzed. Results show threshold voltage shifts and subthreshold leakage, key factors influencing overall circuit behavior at 90nm.
- Propagation Delay Analysis: Increased propagation delay correlates with lower power consumption but at the cost of increased switching times. Delay is critical in determining logic speed and signal integrity in high-speed circuits.
- Noise Margin Impact: Higher noise margin reduces power consumption but may increase delay. Lower noise margin speeds up transitions but may increase power dissipation and susceptibility to noise.

4.2 Limitations:

- Scaling Limitations (90nm Node): As technology scales down, short-channel effects (SCE), leakage, and variability increase, limiting performance improvements.
- Trade-offs in Leakage Reduction: Techniques like the stack approach lower leakage but may increase delay and area. A trade-off exists between power savings and speed.
- Parasitic and Interconnect Delays: At 90nm, parasitic elements become more pronounced, affecting performance. Complex layout techniques are required to mitigate parasitic influences.
- Simulation Complexity: Simulations at the 90nm node require detailed models and high computational resources to achieve accurate predictions.
- Limited Experimental Validation: Results are based on simulations, which may not fully capture fabrication-related variability. Real-world fabrication may introduce additional deviations.

4.3 Future Work:

Sensitivity of delay parameters with respect to NAND and NOR gates and analyzing power consumed with respect to device parameters.

CONCLUSION

In conclusion, the detailed analysis of CMOS performance factors and delay sensitivity, using simulations in Cadence Virtuoso, provides valuable insights into how various device parameters affect circuit performance. Capacitance plays a significant role in increasing delay, as larger load capacitances slow down the switching process. Lowering the threshold voltage reduces delay by allowing faster transistor switching, while reducing the power supply voltage increases delay due to weaker drive strength. Channel width has a complex impact: increasing NMOS width can increase delay due to secondary effects, while increasing PMOS width improves current drive and reduces delay. Longer channel lengths in PMOS transistors cause a significant increase in delay due to lower hole mobility. Finally, thinner gate oxide increases delay by increasing gate capacitance, resulting in slower charging/discharging times. These findings emphasize the importance of optimizing these parameters to achieve efficient and high-performance CMOS circuit designs. Simulation tools like Cadence Virtuoso enable a deeper understanding and help guide these optimizations.

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