Study of Temperature Dependency on MOSFET Parameter using MATLAB

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Abstract – *The massive increase of transistor per die leads to temperature variations that alter the speed, power across the chip and reliability of the circuit. To design a highly reliable and cost competitive system used for high temperature application requires meticulous consideration in thermal area and also electrical area. Over designing and under designing of the circuit leads to undesirable effects. Improper design of system increases cost, weight, overheating and even system failure. In order to design a highly reliable and optimized system for high temperature applications require proper thermal analysis. The various parameters of MOSFET that affects the temperature are bandgap, threshold voltage, contact region resistance, sub threshold leakage current, carrier mobility etc. This study is mainly focused on mathematical modelling of temperature variation in threshold voltage, subthreshold leakage current, source to drain on resistance and overall effect of DC characteristics of MOSFET.*

Key Words: MOSFET, Mathematical modelling, Threshold voltage, subthreshold leakage current, Saturation velocity

1. INTRODUCTION

Since the invention of transistors, the last five decades have witnessed an increase in performance enhancing of electronic devices on a wide variety of automotive, military, aerospace and other industrial and commercial high temperature applications. MOSFET device scaling plays a crucial role in the rapid development of the semiconductor industry. The cost per device and/or per function have been greatly reduced, which is one of the root reason for the widespread adoption of electronics devices. When the number of transistors per die increases the heat dissipation occurring within the chip increases. This effect is called self-heating effect. It leads to large current, greater junction temperature and can result in thermal runaway and even ultimately rendering the device useless. There are a number of factors both inside and outside the semiconductor that resist the high-temperature operation of semiconductor electronic devices and circuits. Proper understanding of these factors is crucial in determining high-temperature applications.

The MOSFET device characteristics and circuit behaviour that changes with the increase in temperature can be predicted and simulated with a suitable model. Precise modelling of temperature dependency of MOSFET parameter have great importance. A study of the impact of temperature on some of the parameters of MOSFET like threshold voltage, subthreshold leakage current, saturation velocity, are done by using MATLAB and the variations of MOSFET dc characteristics are analysed

2. THRESHOLD VOLTAGE

Threshold voltage (Vth or Vtn) influences the static and dynamic modes of operations of the MOSFET. In digital circuits the threshold voltage is usually generalized as 20% of the supply voltage while the typical values of threshold voltage varies from 0.5-1.5V and it is perhaps the most variable parameter of a MOS transistor. Moore's law is kept on the go by transistor miniaturization along with increasing packing densities. This leads to densely packed VLSI and ULSI circuits, the major drawback of this high density circuits is the intense heat generated as they operate usually at high temperatures. This results in degradation of the subthreshold slope of the device and increasing the power dissipation via off state leakage. These factors leads to performance degradation of the device and leads to integration issues.

Threshold voltage is the critical parameter that decides the transistor operation. Almost all the operational characteristics of the transistor depends on the Vth. Even transistor descriptions are made in terms of threshold voltage, variations in threshold voltage causes severe variations, mainly in the operational frequency, in some cases operational frequency may vary up to 30% within the same chip. Threshold voltage variations also leads to increased leakage current that degrades the overall performance of the device in terms of increased power dissipation.

The basic MOS current equation gives the drain current and how it is related to gate to source voltage (VGS) and Vth .This reveals that MOSFET current–voltage characteristics are proportional to the square of the difference of gate voltage and threshold voltage [1]. A very small change in the threshold voltage can have a great impact on the output characteristics as it has a squared effect, hence it is important to accurately measure the threshold voltage that changes with the change in temperature of operation.

Mathematical modelling of Vth can be done by manipulating the physical properties of the transistor such as gate metal, channel doping, oxide thickness and pocket implants [2]. Based on these physical quantities one can derive analytical expressions for the threshold voltage, [3]

$$Vtn = Vto + \gamma(\sqrt{v_{sb} + 2\emptyset f}) - \sqrt{2\emptyset f}$$

(1)

$$\gamma = \frac{tox}{\varepsilon ox}\sqrt{2q\varepsilon_{si}Na} \qquad (2)$$

$$\emptyset f = \frac{KT}{q} ln \frac{Na}{Ni} \qquad (3)$$

The intrinsic carrier concentration Ni varies with temperature and is given by Eq.

$$Ni = (N_c N_V)^{1/2} \exp(-{}^{E_g}/_{2kT}) \qquad (4)$$

where *Nc* and *Nv* are the density of states in the conduction and the valence band and is given by

$$N_c \cong 1.73 \times 10^{16} T^{3/2} \qquad (5)$$

$$N_v \cong 4.8 \times 10^{15} T^{3/2} \qquad (6)$$

$\emptyset f$ is the fermi potential of the body which increases with the decrease in temperature. *Ni* is the carrier concentration of intrinsic silicon, *NA* is the substrate doping concentration and KT/q=v_t is the temperature dependant potential. γ represents the body effect parameter, *q* the charge of an electron and *εox* is the permittivity of oxide

The electron concentration in the channel becomes equal to the hole concentration in the substrate when the voltage drop from channel to substrate is equal to two times the fermi potential and this is when the channel is defined as inverted [4]. When no substrate biasing is applied, ie at *VSB*=0 the threshold voltage is represented as *Vto.* From the *Vt* verses temperature characteristics it is clear that on lowering the temperature the threshold voltage decreases and they have a linear relationship. So operating at lower temperature will be of advantage for MOS device operations as the threshold will be low and hence faster operations becomes possible[5]

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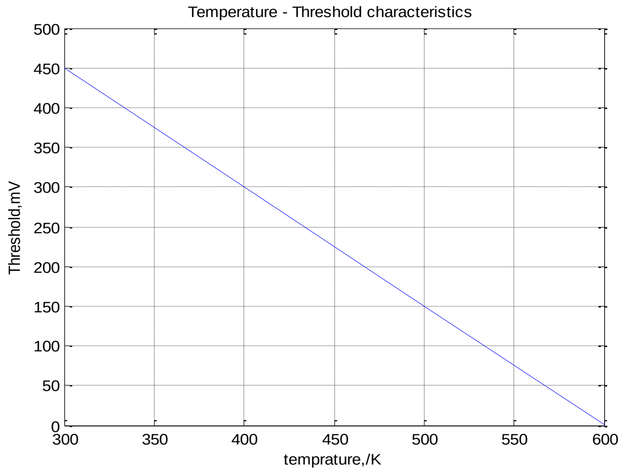

Fig 1. Temperature-Threshold Characteristics

3. SUBTHRESHOLD LEAKAGE CURRENT

Subthreshold leakage current can be used in case of low power devices like TFETs FINFETs etc [6]. But in normal transistors this leakage problem creates serious issues as it leads to power dissipation in the off state condition. As temperature rises, the threshold voltage decreases and the subthreshold leakage current increases exponentially with increase in temperature. So this leakage becomes a severe problem in the case of devices operating at high temperatures. So leakage current can become a limiting factor in the temperature functionality of MOSFETs.

The subthreshold leakage, usually abbreviated as I_{ds} depends exponentially on temperature. The relation or the dependence of leakage current with operating temperature is given by the following expressions [7]

$$I_{ds} = I_{ds0} e^{\frac{v_{gs} - V_t}{n \times vt}} \left(1 - e^{\frac{-V_{ds}}{vt}}\right) \qquad (7)$$

Where,

$$I_{ds0} = \beta vt^2 e^{1.8} \qquad (8)$$

$$V_t = V_t(T_r) - k_{vt}(T - T_r) \qquad (9)$$

$$v_t = \frac{KT}{q} \qquad (10)$$

$$\beta = \frac{\mu_n \times Cox \times W}{L} \qquad (11)$$

$$\mu_n = \mu(T_r)(\frac{T}{T_r})^{-k_\mu} \qquad (12)$$

V_t is the threshold voltage v_t is the thermal voltage, μ_n denote mobility of carriers. $k\mu$ is the Fitting parameter, v_{gs} is the gate to source voltage, V_{ds} is the drain to source voltage, T denotes temperature in Kelvin, *q* the charge of an electron, Cox is the oxide thickness, and W &L are the width and length of the device,

The stand by power of a device depends on the subthreshold leakage current, as it is related exponentially to the temperature. Stand by power also increases exponentially with the increase in temperature. This exponential rise in the subthreshold behavior is due to the exponential dependence of the minority charge carriers and their density. The I_{ds} exponentially rises with temperature as well as the supply voltage. So in general to go for reducing the leakage problems, scaling down of the supply voltage is done [8-9].

The exponential rise in the leakage current is shown in Fig 2. This is the basic limitation of the MOSFET that is as scaling is done the OFF current increases exponentially leading to increased power dissipations and limiting the temperature based functionality of the device. The Fig 2 shows that at room temperature in the case of MOSFET, the leakage current that is I_{ds} is approximately equal to 1mA which is negligible and as the temperature increases, the leakage increases leading to increased OFF state current or increased stand by power. At 400K the subthreshold current is 25mA which is a very high value so this limits the temperature based functionality of the device .Beyond this 400K the normal generalization is made as when the temperature is increased by 10 degrees or 10K the leakage current gets doubled

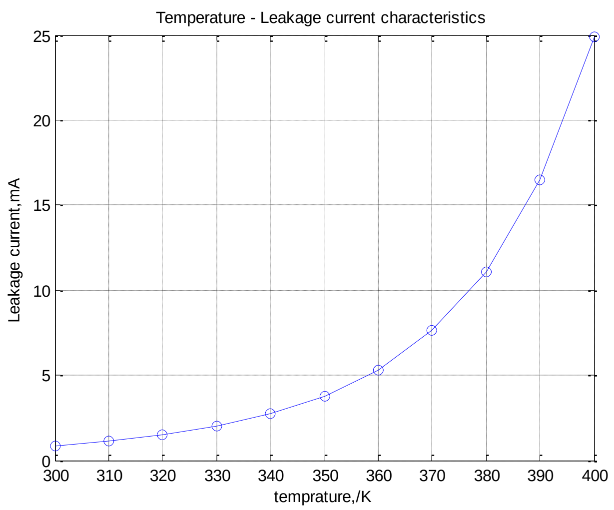

Fig 2. Temperature-Leakage current Characteristics

4. SOURCE TO DRAIN ON RESISTANCE

The study of temperature dependency on source to drain resistance of MOSFET is highly relevant because it determines the maximum current rating and loss. In a MOSFET source to drain ON resistance may be defined as the total resistance between source and drain during the ON condition [10]. In order to minimize the source to drain ON resistance, trench technique and integrity of the chip IS used. The source to drain ON resistance of MOSFET are given by the equation 13[11]

$$RDS\ (on) = RN^{+} + RCH + RA + Rj + RD + RS \quad (13)$$

Where, RN^{+} denotes the resistance between source region and N+ diffusion region. This parameter can be ignored in high voltage MOSFETs. RCH is the channel resistance. The factors depending on channel resistance are ratio of channel width to the length, the thickness of oxide, and the gate drive voltage. RA indicates the accumulation region resistance which is depended on the mobility of the carriers at the surface. RJ is the resistance between N^{-} epi regions between the P-bodies. RD is the resistance in-between top of the substrate and p body. The resistance of substrate region is indicated by RS.

Source to drain ON resistance have positive temperature coefficient. This is because mobility of carriers (holes and electrons) decreases with increase in temperature [12]. The temperature effect of source to drain on resistance is given by the equation 14

$$R_{DS(on)}(T) = R_{DS(on)}(25°C)\left(\frac{T}{300}\right)^{n} \quad (14)$$

Where n denotes the fitting parameter, for Si the value is 2.3 and T is the absolute temperature. Modelling of source to drain ON resistance is very important because it directly depends on device stability and paralleling [13]. The Fig 3 shows the effect of temperature variation on drain to source ON resistance and the increases is almost linear with increase in temperature. This change affects threshold voltage and mobility of the circuit. This lead to reduced speed of operation of the circuit [14].

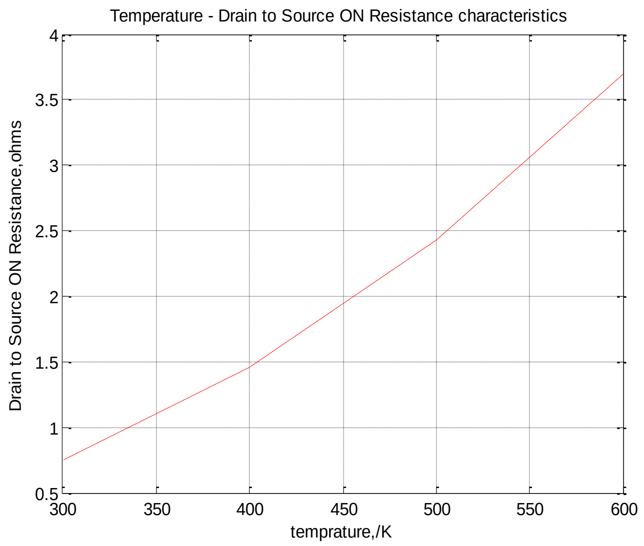

Fig 3. Temperature-Drain to source ON resistance Characteristics

5. MOSFET DC CHARACTERISTICS

The temperature dependency of various parameters on the MOSFET causes variation in dc characteristics. At higher values of gate to source voltage, the drain current decreases with increase in temperature, ie, the MOSFET exhibits negative temperature coefficient at higher values of gate to source voltage. At lower gate to source voltages, the current increases with temperature. Thus the ON current decreases with temperature and OFF current or leakage current increases with temperature, hence the circuit performance is worst at high temperature [7]. The variation of MOSFET I-V characteristics with various temperatures is plotted in fig 4. This shift in dc characteristics affect overall performance of the system.

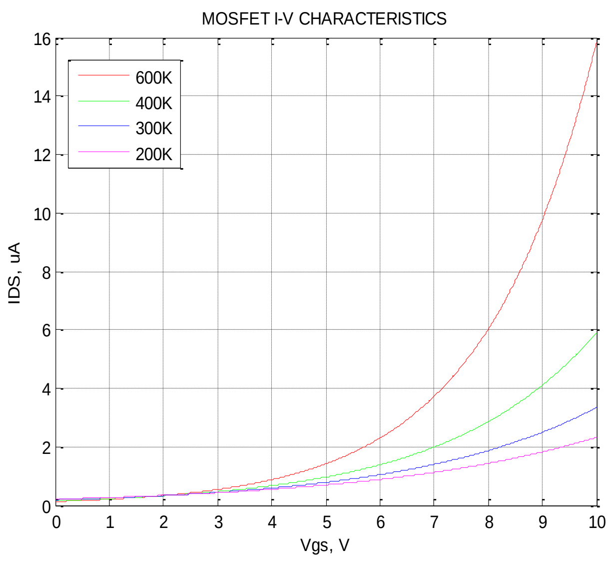

Fig 4. MOSFET I-V Characteristics with various temperature

6. CONCLUSION

An analytical study of MOSFET has been done. Temperature dependence of various MOSFET parameters like threshold voltage, subthreshold leakage current, and source to drain ON resistance are analysed. Both the negative and positive temperature dependence are found out and their diverse effects are analysed. Threshold voltage has negative temperature dependence, subthreshold leakage current and source to drain ON resistance increases with temperature. Effects of temperature dependent parameters on MOSFET DC characteristics are also analysed by plotting with MATLAB. The study of these temperature effects play a major role in designing military grade ICs.

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