14. LECTURE 14: VOLTAGE DEPENDENT HCI

14.1 Review/Background:

We will talk about hot carrier degradation. This is the second topic of the state of four. We discussed about NBTI in previous lectures. In each reliability problem we talk about 4 aspects. First of all how the time extrapolation goes. In some cases can be described by power law like NBTI and sometimes the characteristic could saturate and describe by universal relationship. Also we need to think about frequency and duty cycle dependencies, since we should know the transistors will be off like when the computers goes to sleep. Finally, voltage and temperature accelerations are the other aspects.

From the previous lectures we have seen that under normal operating condition, it takes a long period of time to observe any degradation due to HCI. So in order to characterize HCI degradation, accelerated test is performed at higher voltages. Later these data are extrapolated to predict lifetime at normal operating condition. But for making a good projection, the underlying physical model of voltage acceleration must be known accurately.

We discussed about the physics of hot carrier degradation in the last class. Today's topic is voltage acceleration. If you have two different voltages, for example 3 volts and 2.5 volts then how you can extrapolate it in 1 volt.

We will discuss more about other theories in HCI like Monte Carlo and Universal Scaling. Temperature dependence of HCI degradation will be covered in the next lectures.

14.2 Voltage Acceleration

We are plotting time vs. degradation in a log-log plot. And these experimented the dash line in the graph is for a short time maybe few hours. And then essentially we extrapolated. If it could be a power law like NBTI $t^{1/6}$ then it become simple, but of

course you need to validate $t^{1/6}$ during long period of time. Between all natural phenomena that we know, NBTI power exponent is the most robust that in terms of going about 8-10 orders of magnitude (nothing similar in physics) and it could saturate also. Generally it could make a problem if we cannot construct the bended curve. (Hu, solid State Circuits, 1985)

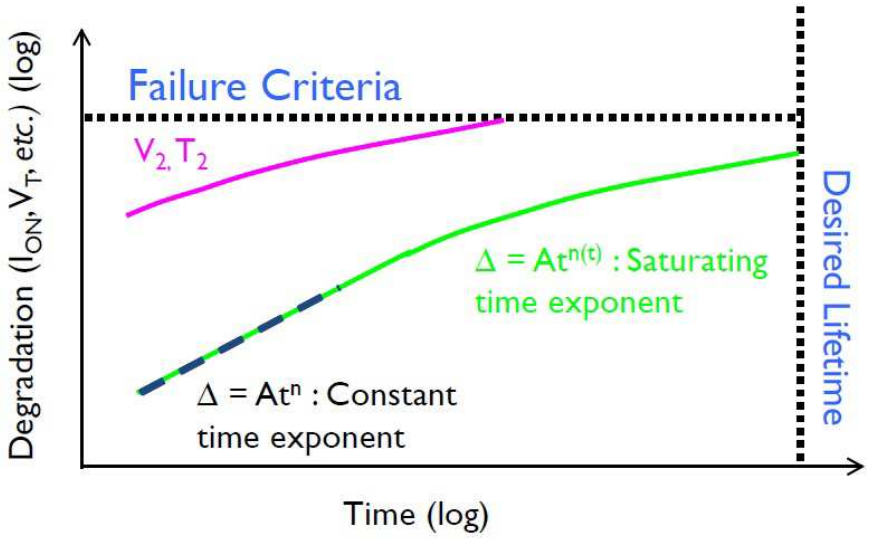

Figure. 14.1. Time vs. Degradation in log-log plot

14.3 Methods for HCI Voltage Acceleration

There are three methods for analyzing the physics of voltage acceleration in HCI.

1. Hydrodynamic Model: This is the analytical model where the energy balance equation will be used to derive a relation between device lifetime and stress voltage.

2. Monte Carlo model: Monte-Carlo is a simulation based technique that simulates the trajectories of individual carriers as they move through a device under the influence of electric fields and random scattering forces. Often this is the only type of model possible when the system is complex (for example: short channel transistors).

3. Universal Scaling: As discussed in the last lecture, device lifetime can be obtained directly from the experimental data by universal scaling. Theoretical analysis is needed in order to explain it.

We will explain all these methods in detail in lecture 14. Before that, we want to find out the relation between device lifetime and forward reaction coefficient.

We know that under DC stress, the number of Si-H bonds that got broken can be written as:

$$N_{IT} = \left(\frac{\pi}{3}\frac{K_f N_0}{K_R}\right)^{1/2} (D_H t)^{1/2} \quad \text{(for H model)} \tag{14.1}$$

$$= \left(\frac{\pi}{6}\frac{K_f N_0}{K_R}\right)^{2/3} \left(D_{H_2} t\right)^{1/3} \quad \text{(for } H_2 \text{ model)}$$

Here, N_0,which is the total number of Si-H bonds, is field independent, the diffusion coefficients $D_H$and D_{H_2} are also field independent as H and H_2both are neutral species, k_r is assumed to be field independent to the first order. So the forward reaction coefficient k_f (bond dissociation rate) is the only field dependent parameter here. Now, if the device lifetime t_0 is defined as the time required reaching a certain level of degradation N_{IT}^{Crit}, we can say from (14.1)

$$K_F^m t_0^n \propto N_{IT}^{crit} \tag{14.2}$$

$$t_0(V_D) \propto \left[\frac{1}{k_F(V_D)}\right]^{m/n}$$

$$K_F = C \times I_G^{(e)}, I_G^{(h)},$$

14.4 Hydrodynamic Model

Therefore voltage dependence of t_0 is encapsulated in voltage dependence of k_f. It is very difficult to solve the Boltzmann transport equation (BTE) directly. So

approximate solution based on solution of moments of BTE is remarkably instructive. These balance or conservation equations that are derived from the BTE have a very clear physical interpretation as we will see in a minute from the "Energy Balance Equation" discussed below. They are known as "Hydrodynamic equations" because of their similarity to the equations commonly used to analyze fluid flow. Drift-diffusion equation will not be applicable here because drift-diffusion equation is valid when gradients in carrier temperature are gentle i.e., carriers are in thermal equilibrium. But ∇Te is not small in case of HCI (temperature of the carriers causing impact ionization is much higher). One thing must be pointed out here there is no restriction of applying drift diffusion equation under low field near equilibrium conditions and also under high field conditions when gradients in carrier temperature are not large [1].

14.5 Electron/Hole Temperature: Balance Equation

In this part we will think about a small region marked green in the **Figure. 14.2** for the conduction band. We know the long channel current is:

$$J_n = \frac{1}{A}\frac{C_0\mu_e}{L_c}(V_G - V_{TH})^{\alpha} \qquad 14.3$$

$$1 < \alpha < 2$$

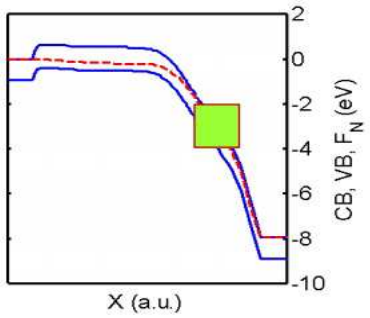

Figure. 14.2. Selected box in the conduction band

Also there is a balance equation for the electrons in terms of its energy flux. When you have a little box of electron $J_n \times E_x$ is the amount of energy you are giving to it. Also W is the energy, so the final term $\left(\frac{W-W^0}{\tau_e}\right)$ in the formula (14.4) is showing, if you

do not add electric field to a hot electron, finally it will settle down to the lattice temperature and the term is calculating how fast the electron will relax. So in the steady state the energy balance equation is:

$$0 = -\frac{d}{dx}\left[(W + nK_BT_e)v - \kappa\frac{dT_e}{dx}\right] + (J_n \times E_x) - \left(\frac{W - W^0}{\tau_e}\right) \quad 14.4$$

Here,
$(W + nK_BT_e)v$: The self energy flux
$\kappa\frac{dT_e}{dx}$: Work against pressure (Thermal diffusion between electrons)
$\left(\frac{W-W^0}{\tau_e}\right)$: Thermal diffusion between electrons and lattice (Energy relaxation term)

W in the pinched-off region can be expressed as,

$$W = \frac{3}{2}nK_BT_e + \frac{1}{2}nm^2v^2 \approx \frac{3}{2}nK_BT_e \quad 14.5$$

Here,
n= total number of electrons = I_D/V_{sat}
T_e= The local temperature of electrons
nm^2v^2 =The total kinetic energy (Assumed to be very small for 180nm or higher node technology)

In Eq. (**Error! Reference source not found.**), $J_n = qnv_{sat}$ is the drift current, where $v_{sat} = \sqrt{\frac{\hbar\omega}{m^*}}$. Thermal diffusion term $\kappa\frac{dT_e}{dx}$ is neglected, W^0 term is also neglected since $W^0 = \frac{3}{2}K_BT_{lattice}$ is small with respect to W ($T_L << T_e$). In steady state, the left hand side of the equation is zero.

Putting all these in (14.4), we get,

$$-\frac{d}{dx}\left[\frac{5}{2}nK_BT_ev\right]+qnv_{sat}E_x-\frac{3}{2}n\frac{K_BT_e}{\tau_e}=0 \qquad 14.6$$

In the (14.7) $E_x(x`)$ shows from $x`$ to x how the electron

$$\frac{K_BT_e}{q}=\frac{2}{5}\int_0^x E_x(x`)e^{\frac{-3(x-x`)}{5\,\tau_e v_{sat}}}dx`=\frac{3}{2}(\tau_e v_{sat})E_x\equiv\lambda_eE_x \qquad 14.7$$

14.6 Calculating Electric field

Remember that for HCI degradation, we are interested only in the saturated regime ($V_D \geq V_G$). In this regime, drain current I_D can be written in the form.

$$I_D=\frac{C_0\mu_e}{L_c}(V_G-V_T)^\alpha \qquad 14.8$$

where $\alpha \sim 1\text{-}2$. In linear regime, 1D potential can be determined if current in each section is continuous. Then integrating up to any position x, we can get the following equation below pinch off [2].

$$\frac{x}{L_c}=\frac{(V_G-V_T)V-\frac{V^2}{2}}{(V_G-V_T)V_D-\frac{V_D^2}{2}} \qquad 14.9$$

In this equation, V_G, V_{th}, V_D, L_c all parameters are known. So if we input any position x, we will be able to solve the quadratic equation and know the local potential V. But equation (14.9) holds below pinch off. Above pinch off i.e. in current saturation regime ($V_D > V_G$), local potential is given by

$$V(x)=V_{Dsat}+U_0e^{x/l}$$

14.10

Where V_{Dsat} is the saturation voltage and, l the length from pinch off point to the drain region [3]. Corresponding local electric field can be obtained by taking derivative of $V(x)$.

$$E_x(x) = dV/dx = U_0 e^{x/l}/l \qquad 14.11$$

Equation (14.10) will be used in (14.8) to calculate the local temperature of electron in the pinch off region.

Position dependent gate current

In the beginning of the channel carriers are not too hot and they are close to lattice temperature, so few of them can go through the barrier. But closer to the drain, they will get hotter and so more can jump over the barrier. I_G results from thermionic emission of hot carriers along the channel.

So, I_G can be calculated by integrating over all positions in the pinch off region. Region other than pinch off is not considered as electric field there is very small. (14.12)

$$I_G = \int_0^1 q n_0 \times \left(\frac{K_B T_e(x)}{2\pi m^*}\right)^{1/2} \times e^{\frac{\Phi_e}{K_B T_e(x)}} dx \qquad 14.12$$

Here Φ_e is the barrier height which is approximately 3.1eV for SiO_2. From Eq. (14.12) we see that as temperature rises, number of electrons going over the barrier increases as expected.

The qn_0 term in Eq. (14.10) is constant and can be replaced with I_D/v_{sat} and $K_B T_e$ can be replaced by $q\varepsilon_x\lambda_e$ from Eq. (14.7). Applying these simplifications, Eq. (14.10) can be rewritten as:

$$= \left[\frac{I_D}{V_{sat}}\right] \int_0^1 \left(\frac{K_B T_e(x)}{2\pi m^*}\right)^{1/2} e^{\frac{\Phi_e}{qE_x\lambda_x}} dx \qquad 14.13$$

In this integration, both T_e and $\varepsilon_x$are changing with respect to x. But since the function has an exponential form which indicates that most of the field is dropped near the drain edge, the integration can be further simplified by "saddle point integration". Saddle point integration is useful for functions having a peak. By employing the following integral

$$\int_a^b e^{Mf(x)} dx = \sqrt{\frac{2\pi}{M|f''(x_0)|}} e^{Mf(x_0)} \; as \; M \to \infty \qquad 14.14$$

So by using Eq. (14.14) we can solve the Eq. (14.13) and get:

$$\frac{I_D}{v_{sat}} \left[l \sqrt{\frac{qE_m\lambda_e}{m^*} \frac{U_0 q}{\phi_e} \frac{\lambda_e}{l}} \right] e^{\frac{-\Phi_e}{qE_m\lambda_e}} \qquad 14.15$$

By getting logarithm from both sides of the Eq. (14.15) we will get:

$$\log\left(\frac{I_G}{I_D}\right) = \frac{\Phi_e}{qE_m\lambda_e} + c. \qquad 14.16$$

Here E_m is the maximum electric field which can be calculated in the following way,

$$V_x = V_{Dsat} + U_0 e^{x/l}$$

$$E_x = U_0 e^{x/l}/l \equiv (V_x - V_{Dsat})/l$$

$$E_m = (V_D - V_{Dsat})/l$$

If we put all these in Eq. (14.12) we get:

$$I_G \propto \frac{I_D}{V_{sat}} e^{-(\Phi_e l/q\lambda_e)/(V_D - V_{sat})} \approx \frac{I_D}{V_{sat}} e^{\mathrm{B}/V_D} \quad (14.17)$$

So by this equation we can relate I_G with V_D.

14.7 Hot Carrier Lifetime

From Eq. (14.2)we know

$$t_0(V_G, V_D) \propto K_f(V_G, V_D)^{-m/n}$$

Since $K_f \propto I_G$ from Eq. (**Error! Reference source not found.**) and I_G can be written in terms of V_D in Eq. (14.17) we have:

$$t_0 \sim \frac{1}{K_f(V_G, V_D)} = \frac{A}{I_G} = \frac{Av_{sat}}{I_D e^{-B/(V_D - V_{D,sat})}} \quad (14.18)$$

This is the relation between t_0 and applied voltage stress V_D. This will be used along with experimentally measured data to get device lifetime at low operating voltage.

From Eq. (14.18), we get by cross multiplying

$$I_D(V_G, V_D) \times t_0 \sim Av_{sat} e^{B/(V_D - V_{D,sat})}$$

If we take logarithm from the both side of the equation we get

$$\ln(I_D \times t_0) \sim \ln Av_{sat} + B/(V_D - V_{D,sat}) \quad (14.19)$$

By determining different it for several different voltages you can find B factor experimentally.

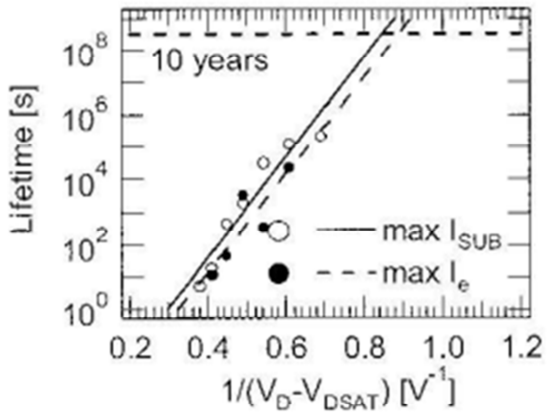

Figure. 14.3. Lifetime Vs $1/(V_D - V_{D,sat})$

14.8 Rate of Impact Ionization

Impact ionization means the electron with enough kinetic energy can knock a bound electron out of its bound state in the valance band and promote it to a state in the conduction band, creating electron hole pair.

Here Φ_i is the barrier means how much energy do you need in order to knock that electron from valance band to conduction band.

$$For\ E > \Phi_i$$

$$\alpha_{ii} \approx C_i[(E\ /\ \Phi_i\ ) - 1]^{\gamma}$$

$$\Phi_i \approx E_G\left(1 + \frac{m_e}{m_e + m_h}\right) \qquad 14.20$$

$$\Phi_i = 1.75\ eV$$

$$C_i = 10^{12}s - 1$$

$$\gamma = 1 - 2\ (Keldysh)$$

In the Eq. (14.20) if we consider $m_e = m_h$ then we can see that we need at least 1.5 or more to have a large impact ionization.

$$I_{sub} = \int_0^l I_D \,.\, \alpha_{II}(x).\, dx \tag{14.21}$$

$$\alpha_{II}(x) = \alpha_0 e^{\frac{-\Phi_i}{K_B T_e(x)}} \approx \alpha_0 e^{\frac{-\Phi_i}{qE_m\lambda_e}}$$

$$I_{sub} \propto I_D e^{\frac{-\Phi_i}{qE_m\lambda_e}} \tag{14.22}$$

$$\Rightarrow \log\left(\frac{I_{sub}}{I_D}\right) = \frac{\Phi_i}{qE_m\lambda_e} + b$$

Here Φ_i is the threshold for impact ionization. (Hess) (Ridley)

Relation between I_G and I_{sub}

We can derive an equation relating I_G and I_{sub} from Eq. (14.16) and Eq. (14.21).

$$\left.\begin{aligned} log\left(\frac{I_G}{I_D}\right) &= \frac{\Phi_e}{q\mathrm{E}_m\lambda_e} + c. \\ log\left(\frac{I_{sub}}{I_D}\right) &= \frac{\Phi_i}{q\mathrm{E}_m\lambda_e} + b \end{aligned}\right\} \quad \frac{I_G}{I_D} = \left[e^{\frac{\Phi_i}{q\mathrm{E}_m\lambda_e}}\right]^{\frac{\Phi_e}{\Phi_i}} = \left[\frac{I_{sub}}{I_D}\right]^{\frac{\Phi_e}{\Phi_i}} \tag{14.23}$$

Therefore, we see that I_{sub} is fundamentally related to I_G gate tunnel current.

Voltage scaling by substrate current

In order to find the relation between device lifetime t_0 and I_{sub}, we use Eq. (14.19) and Eq. (14.22).

$$t_0(V_G, V_D) = \frac{A}{I_G} = \frac{A}{I_D}\left[\frac{I_D}{I_{sub}}\right]^{\frac{\Phi_e}{\Phi_i}}$$

$$t_0(V_G, V_D) = \frac{A}{I_G} = \frac{A}{I_D}\,\frac{v_{sat}}{e^{-\mathrm{B}/(V_D - V_{D,sat})}} \tag{14.24}$$

The first equation is important because, as stated before, both I_D and I_{sub} can be measured instantly as we apply stress. Therefore, using this equation, device lifetime t_0 can be known almost instantaneously. (Varghese, 2009)

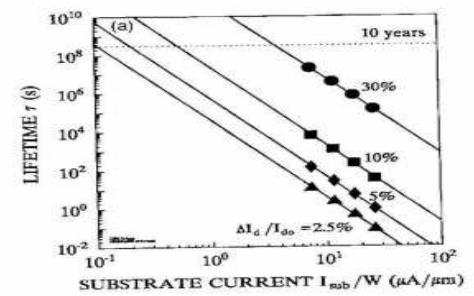

Figure. 14.5 I_{sub} Vs Lifetime t_0

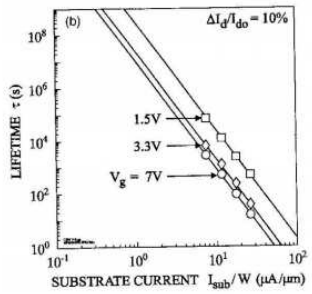

Figure. 14.4 I_{sub} Vs Lifetime t_0

14.9 Relation between I_G and I_{sub}

We can derive an equation relating I_G and I_{sub}

$$\left.\begin{aligned} log\left(\frac{I_G}{I_D}\right) &= \frac{\Phi_e}{q\mathrm{E}_m\lambda_e} + c. \\ log\left(\frac{I_{sub}}{I_D}\right) &= \frac{\Phi_i}{q\mathrm{E}_m\lambda_e} + b \end{aligned}\right\} \quad \frac{I_G}{I_D} = \left[e^{\frac{\Phi_i}{q\mathrm{E}_m\lambda_e}}\right]^{\frac{\Phi_e}{\Phi_i}} = \left[\frac{I_{sub}}{I_D}\right]^{\frac{\Phi_e}{\Phi_i}} \qquad 14.25$$

Therefore, we see that I_{sub} is fundamentally related to I_G gate tunnel current.

14.10 Voltage scaling by substrate current

As we saw in previous section, we can drive relation between device lifetime t_0 and I_{sub}

$$t_0(V_G, V_D) = \frac{A}{I_G} = \frac{A}{I_D}\left[\frac{I_D}{I_{sub}}\right]^{\frac{\Phi_e}{\Phi_i}}$$

$$t_0(V_G, V_D) = \frac{A}{I_G} = \frac{A}{I_D}\,\frac{v_{sat}}{e^{-\mathrm{B}/(V_D - V_{D,sat})}} \qquad 14.26$$

The first equation is important because, as stated before, both I_D and I_{sub} can be measured instantly as we apply stress. Therefore, using this equation, device lifetime t_0 can be known almost instantaneously. (Varghese, 2009)

14.11 Relation between I_{sub} and V_D

From Eq. (14.27), we can also find the relation between I_{sub} and V_D.

$$\left[\frac{I_D}{I_{sub}}\right]^{\frac{\Phi_e}{\Phi_i}} = \frac{\upsilon_{sat}}{e^{-\mathrm{B}/(V_D - V_{D,sat})}} \qquad 14.27$$

This equation is important from experimental point of view. We can find out the values of the constants from (14.3**)** as we apply stress and measure I_{sub}. (**Figure. 14.6**)

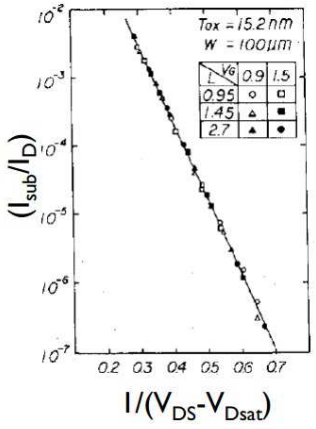

Figure. 14.6 $\frac{I_{sub}}{I_D}$ Vs $\frac{1}{(V_D - V_{D,sat})}$

14.12 Monte-Carlo Method

We can use Monte-Carlo simulation using Newton's equations to accurately estimate electron temperature, number of electron/holes that eventually overcome the potential barrier etc. So the Monte-Carlo theory follows when you are applying electric

field how the position $x(t)$ changes and how the momentum $K(t)$ changes related to the electric field. (J.Bude)

$$k(t) = k_0 - \int_0^t \frac{qE\big(x(\acute{t})\big)}{\hbar} d\acute{t}$$

$$x(t) = x_0 + \int_0^t v\big(x(\acute{t})\big) d\acute{t}$$

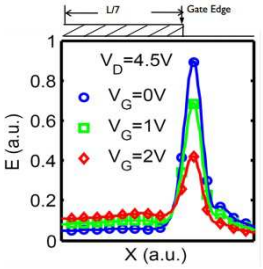

Figure. 14.7 Monte-Carlo sample result

14.13 **Universal scaling**

Universal scaling is an easy way to project high voltage data to get device life time at low operating voltage. We know that any function of the form $f\left(\frac{t}{t_0}\right)$ shows universality. If we have several "degradation/lifetime Vs time" curves at different high stress voltages, we can shift them laterally by different amount to get "degradation Vs time" curve at low operating voltage. These amounts of shifts depend on the stress voltages and give the voltage acceleration factors.

In general the idea of universal scaling is no matter whether you are looking at N_{IT}^{SiH} or N_{IT}^{SiO} at the end you can write it as $f\left(\frac{t}{t_0}\right)$ which t_0 is function of V_G, V_D,etc.

$$N_{IT}^{SiH} = \left(\frac{k_F(V_G, V_D)N_0}{k_R}\right)^{\alpha} t^n \equiv \left(\frac{t}{t_0}\right)^n = f_1\left(\frac{t}{t_0}\right) \qquad 14.28$$

$$N_{IT}^{SiO} = \sum_{E} g(E)\left[1 + e^{-k_F(V_G,V_D)t}\right]dE \equiv f_2\left(\frac{t}{t_0}\right) \quad 14.29$$

$$t_0{}^{-1}(V_G, V_D) = I_G = k\frac{I_D}{W_{eff}}\left[\frac{I_{sub}}{I_D}\right]^{\Phi_e/\Phi_i} \quad 14.30$$

So if we want to determine t_0 we need to find certain N_{it} and use the formulas below:

$$t^*/t_0(V_G, V_D) = f^{-1}(N_{it}^*) = const. \quad 14.31$$

$$t_0(V_G, V_D) \propto t^*(V_G, V_D) \quad 14.32$$

14.14 **Conclusion:**

In this lecture we have discussed about the voltage dependence of HCI. In this part we derived equations of Hydrodynamic Model. We have derived a relation between device lifetime and stress voltage. We also discussed about how substrate current I_{sub} can be used for lifetime projection. We found that for long channel transistors, hydrodynamic solution of balance thermal equation and Monte Carlo both provide reasonable explanation of voltage acceleration factor for HCI degradation. Both demonstrate universal scaling. However we have to use either Monte Carlo simulation or universal scaling for short channel transistors.

References

[1] J. Hu, solid State Circuits, 1985.

[2] K. Hess, semiconductor devices.

[3] Ridley, Quantum Processes.

[4] D. Varghese, Thesis, 2009.