18. DC-IV AND CHARGE PUMPING METHODS

18.1 Review/Background

We have been looking at defect characterization techniques, and we covered the charge-based methods in lecture 17 (CV, Idlin etc.). Another approach to characterize these defects is to see their effect on the electron or hole fluxes. These methods utilize the modifications in electron and hole’s continuity equations for back calculating the trap density, as the generated traps behave as recombination centers. We will discuss about two methods in this chapter, namely DC-IV and Charge Pumping, which are widely used in semiconductor industry and are primarily interface defect sensitive.

18.2 Direct Current-Voltage (DC-IV) method

This method involves monitoring the DC current through the Source-Substrate p-n junction, at low forward biases. At each measurement point, the source-substrate junction is put in small forward bias and the corresponding current values are monitored as a function of stress time. Fig. 17.1a shows the schematic and band diagram of the source-substrate junction at small forward bias ($V_0$) during measurement phase [1].

The whole process is initialized by forward biasing the source-substrate junction with a small voltage ($V_0$) so that a small forward current exits. Then measurement continues by putting the device under stress, i.e. increasing the gate voltage for stress duration and grounding the base. As a result of stress, defects will be generated either in source-substrate junction or throughout the substrate. Finally to probe these newly generated traps, one interrupts the stress, set the gate voltage to zero, and again applies a small forward bias voltage to source-substrate junction and monitors the change in the current. This current is proportional to the number of interface traps.
Once the p-n diode is forward biased with a certain voltage, in this case $V_0$, the quasi Fermi levels are split (Fig. 17.1b). Now if there are a certain number of defects within the depletion region, somewhere inside that region the concentration of electrons and holes will be comparable. Therefore Schottky-Reed-Hall recombination will be maximized. Note that $V_0$ should be large enough, larger splitting of quasi Fermi levels, so it is possible to catch the defects and at the same time it should be small enough so that the primarily diffusion current does not overwhelm the signal (Fig. 17.1b).

Those interface traps created during stress phase, those which are close to midgap will result in higher forward recombination current. Thus, by monitoring the increase in this recombination dominated component of forward current with stress time, we can back calculate the trap density as a function of time. It is important to note that it

Fig. 18.1 (a) Schematic and band diagram of the source-substrate junction at small forward forward bias ($V_0$) during measurement phase, showing the energy distribution interface traps inside depletion region. (b) Current-Voltage characteristics of a diode, showing the trap assisted recombination current with $qV/2k_BT$ slope on a semilog plot [1].
is the low voltage part of the I-V (with ideality factor \( n = 2 \)), which is determined by recombination in the depletion region, and this is the component that will exhibit the signatures of excess trap generation.

18.1.1 **DC-IV method: Derivation**

In order to extract the defect density from measured DC-IV signal, we must derive the correct relationship between the interface trap density \( D_{IT} \) and recombination current \( I_R \). Next, we will present a simple and intuitive way of deriving this relation.
Simple derivation

First, we note that the approximate value of recombination current \( I_R \) can be written in terms of the surface recombination velocity at the semiconductor-oxide interface \( S^* \), simply as:

\[
\frac{I_R}{W} = \Delta n(x = 0) \times S^* \times q \times (x_n + x_p) \propto D_{IT}(x = 0, t) \quad 18.1
\]

Here, \( W \) is the interface width, \( \Delta n \) is the excess injected electron concentration (which is maximum at \( x=0 \)), \( S^* \) is the surface recombination velocity, \( x_n \) and \( x_p \) are the length of depletion region in the n and p materials, respectively. We can see immediately from the equation that the recombination velocity \( S^* \) will be directly proportional to \( D_{IT} \), thus relating it to the current.

There are two important assumptions built into this equation. First, it’s assumed that the recombination at the bulk traps away from the interface is small, compared to the recombination at the oxide interface. This is a reasonable assumption to make, considering the high quality of bulk material. Second, the recombination is assumed to be dominated by the excess carrier concentration at \( x=0 \), where the \( \Delta n \) and \( \Delta p \) values are equal; which is a common assumption for Shockley-Reed-Hall (SRH) recombination current calculation in forward bias.

Knowing that SRH recombination is determined by the \( np \) product and using law of junction we can write:

\[
n \times p = n_i^2 e^{\frac{F_n - F_p}{k_BT}} = n_i^2 e^{\frac{qV_0}{k_BT}} \quad 18.2
\]

At \( x = 0 \), where \( n = p \), and noting that \( n >> n_i \), we can simplify to get:

\[
\Delta n = n - n_0 = n_i (e^{\frac{qV_0}{k_BT}} - 1) \approx n_i e^{\frac{qV_0}{k_BT}} \quad 18.3
\]

Also, the surface recombination velocity can be approximated in terms of defect density \( D_{IT} \) (assumed constant with respect to energy) as:

\[
S^* \approx \sigma_0 v_{th} D_{IT}(F_n - F_p) = \sigma_0 v_{th} D_{IT} qV_0 \quad 18.4
\]
Here, $\sigma_0$ is the capture cross section, and $v_{th}$ is the thermal velocity (both assumed equal for electrons and holes). Finally, we know, from pn junction electrostatics, that the depletion width ($x_n + x_p$) is proportional to $(V_{Bl} - V_0)^{\frac{1}{2}}$, where $V_{Bl}$ is the junction built-in potential.

Putting all the pieces together, from equations (18.1-18.4), we can get a relation between the defect density $D_{IT}$ and the measured recombination current $I_R$, in terms of known quantities, given as:

$$I_R = W \times n_i e^{2k_B T} \times \sigma_0 v_{th} D_{IT} qV_0 \times q \times \text{const.} \sqrt{V_{Bl} - V_0}$$

18.5

Thus, we can back calculate the time dependent defect generation at the interface, by observing the time dependent evolution of $I_R$.

**Spatial profiling**

From the above derivations, it is apparent that the approximate formula for recombination current is accurate enough for most applications. More importantly however, notice that the current is proportional to defect density at the peak position of the recombination profile ($\Delta n(x = 0)$ term in equation 18.1). This suggests that if the peak of recombination can be shifted, we should be able to scan the defect densities at different locations.

This can be done by pressing the gate terminal in service. We can modify the band structure close to the interface by applying a gate field, as shown in Fig. 18.3. As we change VG from $-\nu_e$ to 0 to $+\nu_e$ values, the position where $E_l$ is between $F_N$ and $F_P$ changes from left to right. This position being the dominant contributor in $I_R$, we can get the $D_{IT}$ value at different locations from this sweep.
Quantitatively, we can rewrite equation 18.1 as:

$$\frac{I_R(V_G)}{W} = \Delta n \left( x \cdot n(x(V_G)) = p(x(V_G)) \right) \times s^+ \times q \times (x_n + x_p)$$  

18.6

$$n(x(V_G)) = p(x(V_G)) = n_i^2 e^{qV_G/k_BT}$$  

18.7

Thus, $I_R(V_G) \propto D_{IT}(x(V_G))$, and we can extract the position dependence of defect generation mechanism directly, as shown in Fig. 17.4.
Fig. 18.4 Electric field along x and y axis. As can be seen peak electric field happens close to the gate edge. (b) Spatial hot electron profile along x and y axis.

Fig. 18.5 The position dependent DC-IV signal for hot carrier degradation, thus establishing the localized damage, predicted by theory. Shift of the peak in (b) is a sign that in addition to defect generation; charges are also getting trapped and thus the shift reflects the trapping effects.
18.2 Method No.2: Charge Pumping (CP) method

This is the second flux based method, considered here. This also utilizes the fact that the interface defects created during stress phase lie inside the bandgap, and act as recombination centers for the carriers. The measurement method is shown schematically in Fig. 17.6a; and corresponding energy band diagram is shown in Fig. 17.6b.

During measurement phase, the source and drain junctions are grounded, an alternating voltage signal (square wave) is applied to the gate and the body current is monitored. In this sample case of NMOS transistor, during the positive voltage cycle \(t_{ON}\), the channel is inverted, and electrons from source and drain flood into the channel and get trapped in the interface defects (black arrows in Fig. 17.6a and Fig. 17.6b). During the negative gate voltage cycle \(t_{OFF}\), the transistor goes into accumulation and the traps, filled with electrons, now capture the holes from substrate and electrons flow out through the substrate contact (red arrows in figures Fig. 17.6 a and b.

The result of this periodic population-depopulation of interface traps, through recombination, is a net DC current flow from substrate current \(I_{CP}\). This is due to the fact that, uniquely, we are able to separate the electron and hole capture stages of the trap assisted recombination process. And, since the carriers for these two stages are coming from different contacts (substrate contact for holes and source/drain contacts for electrons), we can see a net DC current through substrate contact.
18.2.1 Qualitative explanation

This can be visualized by looking at the modulation of $E_G$ and $E_V$ levels, with respect to Fermi level $E_F$, due to the application of alternating gate voltage (Fig. 17.7). The four steps of the process are:

(i) $V_G = V^-$: channel is in accumulation ($E_F$ close to $E_V$), and all traps above $E_F$ are empty (marked (1) in Fig. 17.7).
(ii) $V^+ \rightarrow V^-$ transition: $E_i$ starts going down with respect to $E_F$, and the traps get populated by electrons, first through hole emission (marked (2) in Fig. 17.7), and then through capture of channel electrons (marked (3) in Fig. 17.7), as the channel gets inverted.

(iii) $V_G = V^+$: channel is in inversion ($E_F$ is close to $E_C$), and all traps are below ($E_F$ is close to $E_V$) are filled (marked (4) in Fig. 17.7).

(iv) $V^+ \rightarrow V$ transition: $E_i$ starts going up with respect to $E_F$, and the traps are depopulated, first by electron emission (marked (5) in Fig. 17.7), and then through capture of holes from substrate (marked (6) in Fig. 17.7), as the channel goes into accumulation.

Note that the channel electrons populating the traps in steps marked (2,3) in Fig. 17.7, followed by depopulation of these traps by hole capture in steps (5,6), results in a net electron flux from source drain to substrate. This DC electron flux, which is proportional to the trap density inside the bandgap, constitutes the charge pumping current. This current then can be measured to estimate the trap density directly.

Fig. 18.7 Schematic showing the modulation of surface band position with applied AC gate voltage, including the corresponding population-depopulation of traps, from respective contacts.
18.2.2 **Quantitative derivation**

We can derive the relation between trap density \( D_{IT} \) and charge pumping current \( I_{CP} \), by analyzing the fluxes responsible to trap population-depopulation. As shown in Fig. 18.8a, first step is when electron flux \( I_1 \) from source/drain populates the traps. This happens for a \( \Delta \psi_e = (E_{F,inv} - E_{em,h})/q \) voltage range, where the electron capture is the dominant trap population process compared to hole emission (Fig. 18.8a). Then, as \( V_G \) goes down, the electron flux \( I_2 \), flows back to source/drain, due to electron emission (Fig. 18.8a). This happens in voltage range \( \Delta \psi_{ee} = (E_{F,inv} - E_{em,e})/q \), where electron emission to \( E_C \) is the dominant trap depopulation mechanism, compared to hole capture from substrate (Fig. 18.8b). Next, hole capture from source causes hole flux \( I_3 \) to flow from substrate contact (Fig. 18.8a); in the energy range \( \Delta \psi_h = (E_{em,e} - E_{F,acc})/q \), where hole capture dominates over electron emission (Fig. 18.8b). Finally, at the beginning of next transition, in the voltage range \( \Delta \psi_{he} = (E_{em,h} - E_{F,acc})/q \) (Fig. 18.8b), hole emission is dominant and this causes hole flux \( I_4 \) to flow back into the substrate contact (Fig. 18.8a).

![Fig. 18.8 (a) Simplified representation of Fig. 17.7a by fixing the conduction and valance band energies and moving the Fermi level throughout the process. (b) Different current components of (a).](image)

Charge neutrality dictates that the net of electron and hole fluxes must balance. This immediately means that the difference \( I_1 - I_2 \) or \( I_3 - I_4 \) will give us the net carrier flux, and hence the current \( I_{CP} \). Also, the discussion above detailing the energy ranges shows that the traps in the energy range \( E_{em,e} - E_{em,h} \) correspond to \( I_1 - I_2 \), and can be probed by \( I_{CP} \).
We can now write the net charge $Q_{ss}$ that flows between contacts, through the traps in the energy range between $E_{em,e}$ and $E_{em,h}$ as

$$Q_{ss} = \int_{\psi_{min}}^{\psi_{max}} qA_G D_{IT}(E) dE = q^2 A_G \langle D_{IT} \rangle \Delta \psi. \quad \Delta \psi = \psi_{max} - \psi_{min} \quad 18.8$$

Here, $A_G$ is the gate area, $\langle D_{IT} \rangle$ is the average trap density inside the bandgap. Now, the rate of flow of this charge is $I_{CP}$, which is simply given by $Q_{ss}/T_{cycle}$, or:

$$I_{CP} = q^2 A_G \langle D_{IT} \rangle f \times \Delta \psi. \quad 18.9$$

$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{bmatrix} = q^2 A_G \langle D_{IT} \rangle \begin{bmatrix} \Delta \psi_e \\ \Delta \psi_{ee} \\ \Delta \psi_h \\ \Delta \psi_{h,e} \end{bmatrix} \quad 18.10$$

$$I_{S/D} = I_1 - I_2 = q^2 A_G \langle D_{IT} \rangle f \times [\Delta \psi_e - \Delta \psi_{ee}]. \quad 18.11$$

$$I_{S/D} = I_1 - I_2 = q^2 A_G \langle D_{IT} \rangle f \times [E_{em,h} - E_{em,e}]. \quad 18.12$$

where $f$ is the frequency of applied gate voltage signal. Now, from SRH recombination formulation we know that carrier emission rate $\tau_{em}^{-1}$ and capture rate $\tau_c^{-1}$ are related by $\tau_{em}^{-1} = \tau_c^{-1} n_1$ where $n_1 = n_i e^{E_T/k_B T}$, and $E_T$ is the trap energy level. Also, capture rate $\tau_c^{-1} = (v_{th} \sigma)^{-1}$, where $v_{th}$ is the thermal velocity and $\sigma$ is the capture cross section of the trap [2]. Putting these together, we can replace the $\Delta \psi$ in terms of emission times $\tau_{em,e}$ and $\tau_{em,h}$, to write:

$$I_{CP} = 2 q A_G \langle D_{IT} \rangle f k_B T \left[ \ln\left(v_{th} \sqrt{\sigma_{n} \sigma_{p}} n_i \right) + \frac{1}{2} \ln(\tau_{em,e} \tau_{em,h}) \right]. \quad 18.13$$

Notice the factor of 2 in front. Here, $\sigma_n$ and $\tau_{em,e}$ ($\sigma_h$ and $\tau_{em,h}$) are the electron (hole) capture cross sections and emission times, respectively; and $v_{th}$ is the thermal velocity. The $\sigma$ and $v_{th}$ being material parameters are known from literatures; and the only parameters needed for calculating the trap density using equation 18.13 are the emission times. A neat way to get the emission times is to note that the electron (hole)
emission can occur, only during that period of the fall (rise) time, when $V_G$ is between threshold voltage $V_{th}$ and flat band voltage $V_{FB}$. It is only in this window that the electron or hole emission mechanisms dominate, as apparent from Fig. 18.8b. Thus we can write the emission times as:

$$t_{em,e} = \frac{|V_{FB} - V_{th}|}{|V_{Gh} - V_{Gl}|} t_f, \text{and } t_{em,h} = \frac{|V_{FB} - V_{th}|}{|V_{Gh} - V_{Gl}|} t_r; \tag{18.14}$$

where $V_{Gh}$ and $V_{Gl}$ are the high and low values of the gate voltage waveform. Finally, this enables us to write the relationship between charge pumping current $I_{CP}$ and average trap density $<D_{IT}>$ in the following form,

$$I_{CP} = 2qA_G<D_{IT}>f k_B T \left[ \ln\left( v_{th} \sqrt{\sigma_n \sigma_p n_i} \right) + \frac{1}{2} \ln \left( \frac{|V_{FB} - V_{th}|}{|V_{Gh} - V_{Gl}|} \sqrt{t_r t_f} \right) \right]; \tag{18.15}$$

such that all other terms in the equation are known, allowing us to back calculate the $<D_{IT}>$ from measurement.

In the 18.15 we have everything but capture cross section’s values. If we want to exactly find the values of capture’s cross sections for electrons and holes, we should do a series of experiment (Error! Reference source not found.) where we vary the rise and fall time. Then from the results, if we differentiate the CP current with respect to $t_r$ and $t_f$ there would be no dependence on capture cross section anymore and therefore we have everything we want and we can back calculate the exact density of interface traps. We can also find capture cross section once we have $D_{IT}$ and rise and fall time.
18.2.3 **Energy and spatial profiling of traps**

The relationship between energy range scanned \((E_{em,e} - E_{em,h})\), and rise and fall times, through emission times (equations (18.13 18.14)); suggests that by varying \(t_r/t_f\) or frequency \(f\), we can probe different energy ranges inside the gap. This is a powerful tool to explore the energy distribution of traps inside the bandgap directly. It is important to note however, that this method will limit itself to the traps deep inside the bandgap, as the traps closer to EC (EV) will always emit the carriers back to source/drain (substrate), resulting in no charge pumping current [3].

Remember that CP current is only observable where the gate voltage jumps rise from below \(V_{FB}\) to above \(V_{th}\). If traps are close to source and drain, however, the effective threshold and flat band voltages are significantly different. So if you manage to have a gate voltage where its low value is below \(V_{FB}\) but its high value is above the local threshold voltage of the source/drain and less than threshold voltage inside the channel, away from source/drain regions, only traps close to source/drain regions will contribute to CP. Now if the high level of the gate voltage gradually increases, traps within the channel and

\[
I_{CP} = 2q^2 (L \times W) \left( \frac{D_{IT}}{f \times k_B T_L} \right) \ln \left( \frac{V_{FB} - V_{th}}{V_{G,H} - V_{G,L}} \right) \sqrt{t_r t_f}
\]
away from source/drain regions start contributing to $I_{CP}$. As a result, you can find the spatial profile of the traps throughout the channel area (Error! Reference source not found.). One can also show that for NBTI and HCI the following relations are derived:

\[
\Delta I_{CP}(V_{\text{base}}) = \Delta I_{CP,s}(V_{\text{base}}) - \Delta I_{CP}(V_{\text{base}})
\]

\[
\propto \int_{-y_1}^{0} N_{IT}(y) \, dy + \int_{0}^{y_{1,s}} N_{IT,s}(y) \, dy
\]

\[
- \int_{-y_1}^{0} N_{IT}(y) \, dy - \int_{0}^{y_1} N_{IT,s}(y) \, dy
\]

\[
= \int_{0}^{y_{1,s}} \left( N_{IT,s}(y) - N_{IT}(y) \right) \, dy + \int_{y_{1}}^{y_{1,s}} N_{IT}(y) \, dy
\]

\[
= \int_{0}^{y_{1,s}} \Delta N_{IT,s}(y) \, dy + \int_{y_{1}}^{y_{1,s}} N_{IT}(y) \, dy
\]

\[
\uparrow \quad \uparrow
\]

\textit{NBTI stress} \quad \textit{HCI stress}

\[18.16\]

\[18.17\]

\[18.18\]

\[18.19\]

\[18.20\]

Fig. 18.10 Mechanism of using charge pumping to find spatial distribution of traps
18.3 **Bulk trapping at low frequency**

The idea is illustrated in Fig. 18.11. If you do charge pumping at low frequencies (below 1MHz) carriers have enough time to get trapped and then recombined through bulk. As a result, charge pumping is no longer confined to the interface traps. In other words, bulk traps act like a parasitic components and distort the results. In practice, people start charge pumping at really high frequencies, to find interface trap’s density, and then they gradually reduce the frequency, probing traps deep into bulk [4].

![Fig. 18.11 Mechanism of multi-frequency charge pumping to probe traps deep inside the bulk [4].](image)

18.4 **Conclusions**

We covered two most important flux based methods for defect characterization, namely DCIV and CP methods. The advantage of these methods being able to probe interface traps only, coupled with modifications that can profile the spatial and/or energy
distribution of these traps. These two capabilities of CP method, make it a popular characterization choice for interface degradation phenomena like NBTI.

On the flip side these methods require large measurement times, which can cause relaxation effects to contaminate the time characteristics. This required the incorporation of on-the-fly techniques, to augment these methods. For CP method, care has to be taken to keep the frequency is kept high enough, to ensure that there are no bulk traps involved.

18.5 Discussion

1) Between two measurement techniques, which one is easier and why?

DC-IV is simpler, as it does not require additional equipment (e.g. function generator), needed for CP method.

2) In what ways are CP and DCIV methods better at characterizing traps compared to C-V methods?

Unlike CP and DCIV methods which probe only interface traps, CV methods make no distinction between interface and bulk traps. Moreover, spatial (CD & DCIV) and energy (CP only) profiling of traps is not possible using CV methods.

3) What are the problems of using CP, DCIV, C-V methods for NBTI and HCI measurements?

As these methods take a lot of measurement time, the relaxation in NBTI and HCI can corrupt the time characteristics of defect creation.

4) Which method does not suffer from the same problem as CP, DCIV, etc. for NBTI and HCI applications?

On-the-fly methods are needed to alleviate this relaxation problem of CP and DCIV methods.

5) What method would you use to determine the density of midgap states? What about close to interface?
DCIV is best for both the cases, though CP will give similar results too.

6) CP frequency has to be kept relatively high to probe interface traps; can you explain why?

If the CP frequency is low enough, even the bulk traps can get populated-depopulated during the cycle, and we will not be able to isolate the interface trap generation from it.

7) Between two measurement techniques, which one is easier and why?

DC-IV is simpler, as it does not require additional equipment (e.g. function generator), needed for CP method.

8) In what ways are CP and DCIV methods better at characterizing traps compared to C-V methods?

Unlike CP and DCIV methods which probe only interface traps, CV methods make no distinction between interface and bulk traps. Moreover, spatial (CD & DCIV) and energy (CP only) profiling of traps is not possible using CV methods.

9) What are the problems of using CP, DCIV, C-V methods for NBTI and HCI measurements?

As these methods take a lot of measurement time, the relaxation in NBTI and HCI can corrupt the time characteristics of defect creation.

10) Which method does not suffer from the same problem as CP, DCIV, etc. for NBTI and HCI applications?

On-the-fly methods are needed to alleviate this relaxation problem of CP and DCIV methods.

11) What method would you use to determine the density of midgap states? What about close to interface?

DCIV is best for both the cases, though CP will give similar results too.

12) CP frequency has to be kept relatively high to probe interface traps; can you explain why?
If the CP frequency is low enough, even the bulk traps can get populated-depopulated during the cycle, and we will not be able to isolate the interface trap generation from it.

13) Between two measurement techniques, which one is easier and why?

DC-IV is simpler, as it does not require additional equipment (e.g. function generator), needed for CP method.

14) In what ways are CP and DCIV methods better at characterizing traps compared to C-V methods?

Unlike CP and DCIV methods which probe only interface traps, CV methods make no distinction between interface and bulk traps. Moreover, spatial (CD & DCIV) and energy (CP only) profiling of traps is not possible using CV methods.

15) What are the problems of using CP, DCIV, C-V methods for NBTI and HCI measurements?

As these methods take a lot of measurement time, the relaxation in NBTI and HCI can corrupt the time characteristics of defect creation.

16) Which method does not suffer from the same problem as CP, DCIV, etc. for NBTI and HCI applications?

On-the-fly methods are needed to alleviate this relaxation problem of CP and DCIV methods.

17) What method would you use to determine the density of midgap states? What about close to interface?

DCIV is best for both the cases, though CP will give similar results too.

18) CP frequency has to be kept relatively high to probe interface traps; can you explain why?

If the CP frequency is low enough, even the bulk traps can get populated-depopulated during the cycle, and we will not be able to isolate the interface trap generation from it.
18.6 Reference


