EE650R: **Reliability Physics of Nanoelectronic Devices**
Lecture 16: **Charge Pumping and SDR measurements**
Date: **Oct. 18, 2006**
Class Notes: **Nauman Butt**
Review: **Dhanoop Varghese**

16.0 Review/Background:

We have been talking about the measurement techniques for the characterization of Negative Bias Temperature Instability (NBTI) for the past lectures. We divided the measurement techniques into three broad categories which are (i) charge based, (ii) Flux based, and (iii) Spin based methods. We have studied the first two techniques in the previous few lectures. Today we will complete the discussion of charge pumping and will study the third type of measurements which is the spin based technique.

16.1 Charge Pumping (continued form the previous lecture):

In the last lecture, we discussed various currents which flow through the device under test during a charge pumping measurement. We named them I_1, I_2, I_3 and I_4 as shown in the fig. 1.

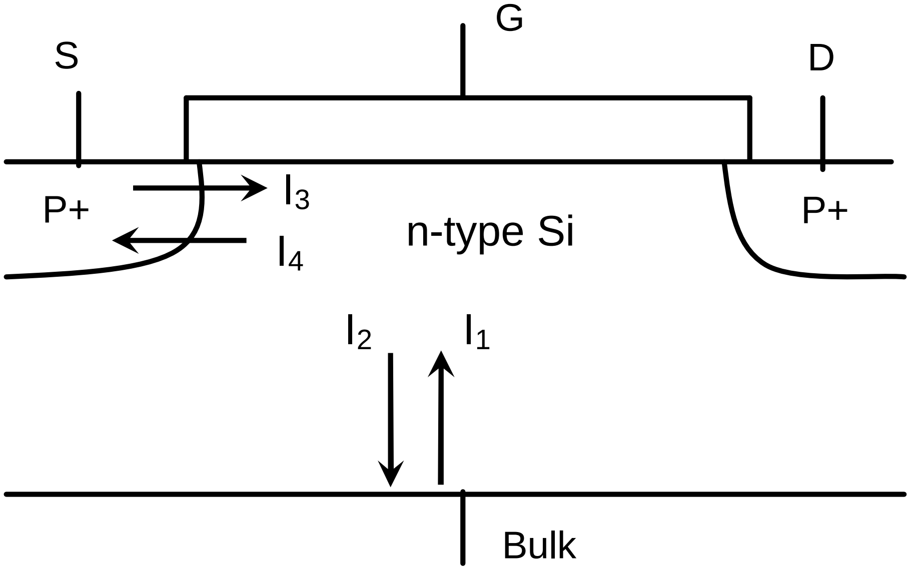


Fig. 1 Directions of different currents during the charge pumping measurement

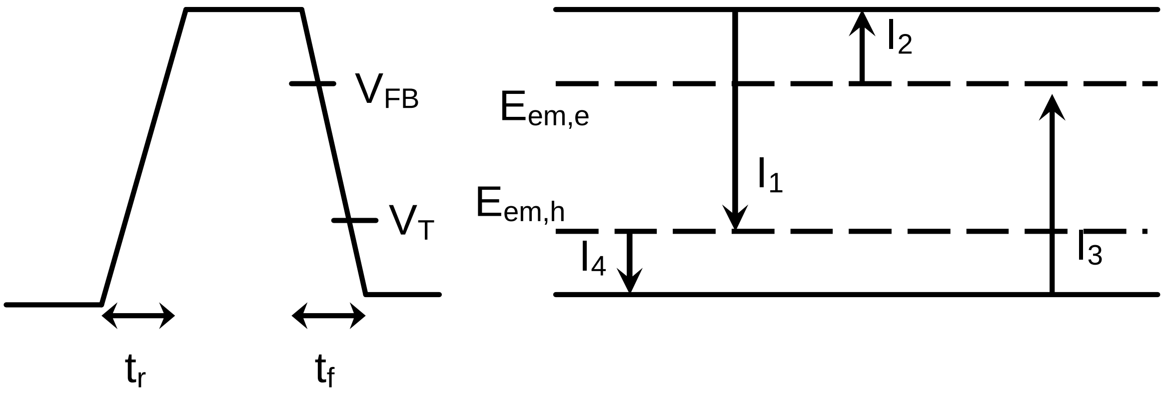


Fig. 2 Gate Voltage pulse (left) and the band diagram (right) illustrating the transitions responsible for the various currents during the charge pumping measurement

In the last lecture, we derived the following expression for the substrate current (I_{sub}):

$$I_{sub} = A_G q^2 D_{IT}\, f\,(E_{em,h} - E_{em,e}) \tag{16.1.1}$$

where D_{IT} is the interface trap density, A_G is the gate area, q is the charge of an electron, $E_{em,e}$ is the energy of electron after emission to the trap and $E_{em,h}$ is the energy of hole after emission to the trap. To compute D_{IT} from measured value of Isub, we will have to derive the expression for $E_{em,h} - E_{em,e}$ based on other known parameters of the system, as discussed below.

Let r_n be the net recombination rate which is given by:

$$\begin{aligned} & r_n = c_n p_T n - e_n n_T = 0 \quad \text{in equilibrium} \\ & e_n = \frac{1}{t_{em,e}} \end{aligned} \tag{16.1.2}$$

where c_n, e_n are the capture and emission coefficients for electrons. p_T, n_T are the empty and filled interface states. n is the density of electrons in the conduction band and $t_{em,e}$ is the time constant for the electron emission.

e_n is given by the relation:

$$e_n = \frac{1}{t_{em,e}} = c_n \frac{p_T}{n_T} n = v_{th} s_0 n_i e^{(E_T^{'} - E_i)/kT} \tag{16.1.3}$$

where v_{th} is the thermal velocity, s_0 is the capture section and $E_T^{'}$ is the trap energy.

The above equation can be simplified to get the expression for $E_{em,e}$

$$\frac{1}{n_i v_{th} t_{em,e} s_0} = e^{(E_T^{'} - E_i)/kT}$$

$$-kT \ln \frac{1}{s_0 v_{th} t_{em,e} n_i} = -(E_T^{'} - E_i)$$

$$kT \ln(s_0 v_{th} t_{em,e} n_i) = -(E_T^{'} - E_i)$$

$$E_T^{'} = E_i - kT \ln(s_0 v_{th} t_{em,e} n_i)$$

$$E_{em,e} = E_i - kT \ln(s_0 v_{th} t_{em,e} n_i) \tag{16.1.4}$$

Similarly for the holes, we can derive:

$$E_{em,h} = E_i + kT \ln(s_0 v_{th} t_{em,e} n_i) \tag{16.1.5}$$

Now we can find the value of $E_{em,e} - E_{em,h}$ by using the above expressions.

$$E_{em,e} - E_{em,h} = kT[\ln(t_{em,e} t_{em,h}) + \ln(s_0^2 v_{th}^2 n_i^2)] \tag{16.1.6}$$

The values of the time constants $t_{em,e}$ and $t_{em,h}$ can be found by looking at the V_G pulse in the fig. 2,

$$t_{em,e} = \left| \frac{V_{FB} - V_T}{\Delta V_G} \right| t_f \tag{16.1.7 a}$$

$$t_{em,h} = \left| \frac{V_{FB} - V_T}{\Delta V_G} \right| t_r \tag{16.1.7 b}$$

Finally we get the following expression:

$$\boxed{E_{em,e} - E_{em,h} = kT[\ln \left| \frac{V_{FB} - V_T}{\Delta V_G} \right|^2 t_r t_f + \ln(s_0^2 v_{th}^2 n_i^2)] \qquad (16.1.8)}$$

Since we know all the parameters in (16.1.8), therefore we can evaluate the difference in emission energies of electrons and holes. Once this is known, Eq. (16.1.1) can be used to calculate the value of D_{IT} from known value charge pumping current, I_{sub}.

16.2 Spin Dependent Recombination (SDR):

This technique is a close variant of Electron Spin Resonance (ESR) and has some similarity to DC-IV technique with respect to biasing configuration. A device is stressed for a certain period of time and the number of D_{IT} generated during the stress is measured by interrupting the stress and using the SRR (Hence SRC is a delay-contaminated measurement technique!).

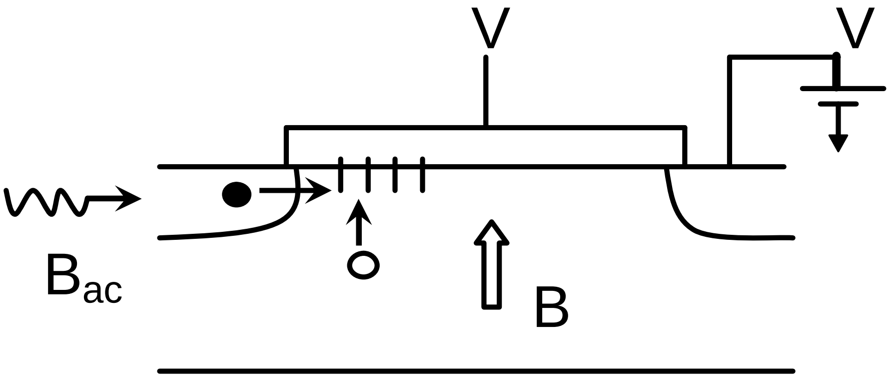


Fig. 3. The cross-section of MOSFET under SDR test

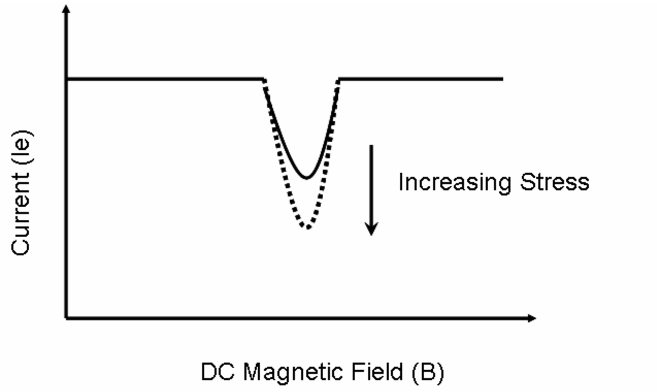
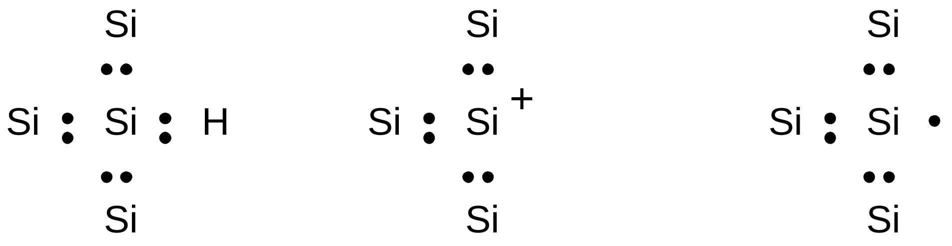


Fig. 4 Drain current as a function of the Applied DC magnetic field

Fig. 3 illustrates the basic concept of SDR. The MOSFET is biased by applying a small drain voltage (V_d) and a gate voltage ($V_g > V_t$) where V_t is the threshold voltage. A drain current (I_e) will flow in the normal condition. Now if we apply a DC magnetic field (B_{dc}) in the vertical direction and ac magnetic field (B_{ac}) of a certain frequency along the channel direction and monitor the magnitude of current by varying B_{dc}, we will see a dip in I_e at a certain value of B_{dc} as illustrated in fig. 4. The magnitude of this I_e dip correlates to the value of interface trap density (N_{it}). The value of B_{dc} corresponding to the I_e dip is unique for Si-H bonds hence this technique is explicitly sensitive to the broken Si-H bonds. In the following sections we will discuss the physical mechanisms involve in this measurement and will derive the mathematical relations for the current as a function of B_{ac}.

16.2.1 Physical mechanisms in SDR measurement:

The broken Si-H bonds behave as donor like impurities. They are positively charged above the Fermi level (E_f) and neutral below E_f, as shown in fig. 5. SDR is sensitive only to those interface traps which are below E_f. Let n_T be the density of traps below E_f. If there is no applied B, the spins of the electrons in the trap states will be randomly aligned. If we apply B_{dc} in the vertical direction, the spins will be aligned this direction as shown in fig. 6. After applying the gate and drain bias, the current will start flowing in the channel. The conduction electrons which have density (n_c) have two spins in each energy state. The electrons in the traps have only up spin because of the applied B_{dc}. Hence the traps can capture the down spin electrons from n_c and fill the states with each state having an up-spin and a down-spin electron according to the Pauli's exclusion principle. The potential energy of the trap will be raised up after the capture of the down-spin an electron and this state is called a Singlet state as shown in fig. 6. The Singlet state will further decompose into the triplet state which has three states with the total spins of S=1, 0 and -1 as shown in fig. 6. The electrons in the triplet state make transitions among the three energy levels but the allowed transitions are only between those states which have the spin difference of 1, i.e $DS = \pm 1$ (For a good discussion of singlet and triplet states, their symmetry properties, and selection rules, you may want to consult S. Gasiorowicz, Quantum Physics, Chapter 15). If there is no applied B_{ac}, then the spontaneous emission from the triplet states will be strong and the triplet will not be a long-lived state. In the presence of B_{ac} there will be a stimulated absorption component among the triplet state which will make the triplet stable for a longer time.



Un-Broken Si-H Bond Broken Si-H Bond (above E_f) Broken Si-H Bond (below E_f)

Fig. 5 The Si-H bond before and after being broken

16.2.2 Mathematical derivation of current vs. magnetic field relation:

Let the initial trap concentration due to the broken Si-H bonds which are below Ef be n_T.

$$n_T = n_{s0} + n^{(+)} + n^{(0)} + n^{(-)} \qquad (16.2.1)$$

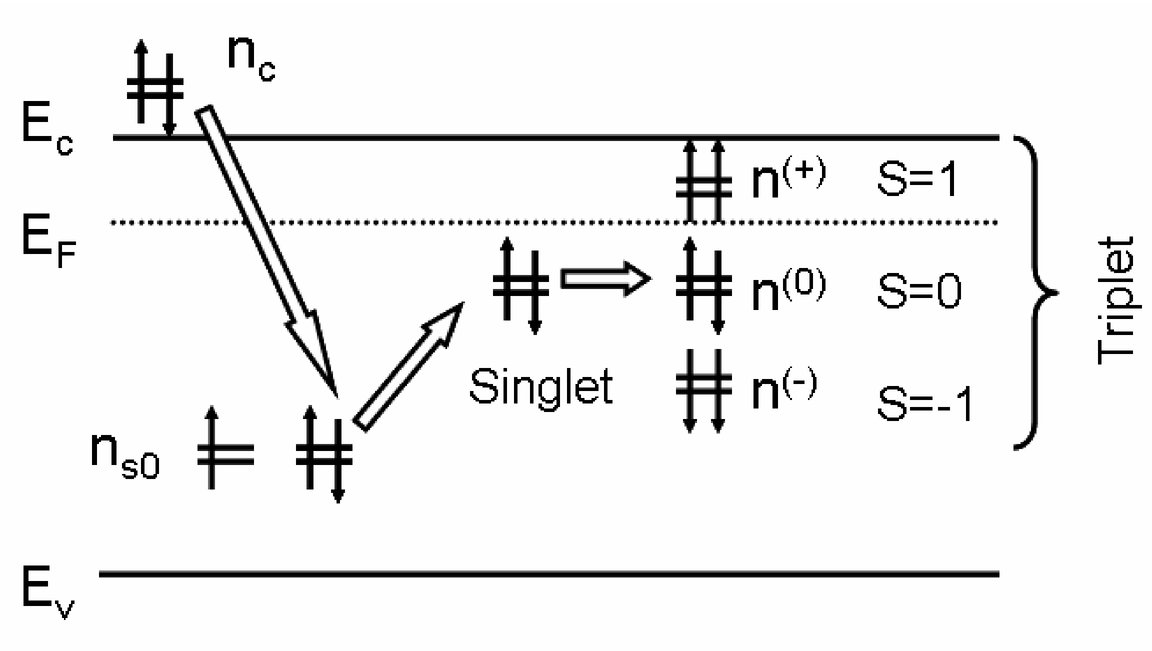


Fig. 6   Band diagram illustrating the mechanisms in SDR measurement

Where n_{s0} is the trap density before applying the magnetic field while $n^{(+)}$, $n^{(0)}$ and $n^{(-)}$ are trap densities of each of the triplet states respectively.

We can write the following set of the rate equations for each of the above component of n_T .

$$\begin{aligned}
\frac{dn_s}{dt} &= \frac{J}{q} - s\, n_c n_{s0} - R n_c \\
\frac{dn^{(+)}}{dt} &= \frac{s\, n_c n_{s0}}{3} - n^{(+)}R - (n^{(+)} - n^{(0)})W - (n^{(+)} - n^{(0)})B_{ac} \\
\frac{dn^{(-)}}{dt} &= \frac{s\, n_c n_{s0}}{3} - n^{(-)}R - (n^{(-)} - n^{(0)})W - (n^{(-)} - n^{(0)})B_{ac} \\
\frac{dn^{(0)}}{dt} &= \frac{s\, n_c n_{s0}}{3} - n^{(0)}R - (n^{(0)} - n^{(-)})W - (n^{(0)} - n^{(+)})W - (n^{(0)} - n^{(+)})B_{ac}
\end{aligned} \tag{16.2.2 a-d}$$

where s is the capture cross-section for the down-spin electrons in conduction band, R is the recombination rate for the direct recombination (without involving the traps), W is the rate of spontaneous emission among the (nearest neighbor) triplet states. These equations can be written only when B_{dc} causes a level-splitting to match B_{ac}, otherwise in general the terms of the equations (proportional to B_{ac}) would not exist. We will notice that we have included 'B_{ac}-dependent' terms for transition from (+) to (0) states, not from (-) to (0). This is because there are other coupling (in addition to B_{dc}) in the system that makes the splitting between (+) and (0) states slightly different from (-) to (0) states. Therefore, typically only pair can couple to the AC magnetic field, while the other does not.

You will also notice that we have no term related to the excited singlet state, because the electrons here decay to ground-state Singlet level or to excited Triplet relative quickly (If you want to know more, you can look up “Level Crossing” to know how states transform from one to the other). Transition from excited Triplet to ground-state Singlet is forbidden except through perturbation like spin-orbit coupling (governs the physics of W). So that these states are long lived and their population governs the dynamics of electron relaxation. So long the electrons are at excited state, the holes from the valence band can not neutralize them – so that fraction of N_{IT} remains inaccessible for recombination. This control over recombination through the magnetic field is at the heart of the SDR process.

In (16.2.2) there are 4 equations with unknowns: n_{s0}, $n^{(+)}$, $n^{(-)}$ and $n^{(0)}$. The solution of above equations gives the following relation between J and B_{ac}:

$$\boxed{\frac{J}{q} = s\, n_c n_{so} + R n_c = \frac{s\, n_c N_T}{1 + \frac{1}{3} s\, n_c F(B)} + R n_c \qquad (16.2.3)}$$

where,

$$F(B) = \frac{a(R+W) + bB_{ac}}{c(R+W) + dB_{ac}}$$

and

$$a = 2R^2 + R + 9W \qquad b = R^0 + 5R + 9W$$

$$c = RR^0 + 2RW + R^0 W \qquad d = RR^0 + 2RW + R^0 W + R^2$$

Fig. (16.2.3) suggests that the changes in J reflects changes in N_T or equivalently D_{IT}.

Now one can ask if it is necessary for the B field to be present here. After all, even with $B_{ac}=0$, we still get a recombination current proportional to N_T and indeed that is the essence of the DC-IV method. However, the magnetic field allows us to tune into only one or other types of bonds (SiH vs. SiO) because they have resonances in different parts of the spectrum. As such, they allow us to isolate the component of D_{IT} due to Si-H related P_b centers alone. As you surely remember that NBTI dynamics is related to the dissociation and annealing kinetics of Si-H bonds at the Si/SiO2 interface.

16.3 Conclusions:

That is all about various NBTI measurement techniques currently being used by various groups. Each explore different facets of the same problem. We will compare and contrast these characteristics in the next class.