Chapter 2

Deep Levels in GaAs

2.1 Introduction

Most of the electronic properties and ultimately a performance of the devices can be altered considerably by the presence of defects.

Depending upon their locations within the device; they can perturb a specific characteristics. In the active region, they decrease or increase the free carriers concentration by trapping or emitting. In the substrate, they can reduce the channel current. This is called the backgating effect which is the subject of the present work.

The simplest defect, is that caused by impurities which involves only a single foreign atom. Depending on their position into the periodic table they can create shallow or deep levels within the band gap. If The foreign atoms belong to the groups of the periodic table closest to that of semiconductor then they tend to create levels very close to band edges. These levels are referred to as Shallow levels while those not belonging to the closest groups in the periodic table to the host lattice; usually create deep levels which may be most simply classified as those which are positioned deeper than expected hydroginic state in the band gap($\approx K_B T$). But in general case, the deep levels may be related to either a chemical impurity or physical defect (Structural defect) see for example [35].

Deep levels may behave as carrier traps or as generation-recombination centers. The importance of a particular level as trap or generation-recombination center is determined by the respective rates at which it captures and/or emits electrons and/or holes. In general if a captured carrier at deep level stays there until it is reemitted back into the band it comes from then the level is classified as a trap. If, however, a carrier of opposite type gets captured on the same level before the first is reemitted then this level is a recombination center since there is an electron-hole recombination [36].

Some deep levels are deliberately introduced to alter a device characteristics, and since they are traps or recombination centers they can play a different roles. As recombination centers, deep levels may beneficial or detrimental. An example of desirable effects is that the switching time may reduced by addition of Gold (Au) or platinum (Pt) to Silicon. These are known as minority carrier lifetime killers since they reduce the free carrier lifetime and increase the switching frequency [3]. As traps, one of the major beneficial effects is adding

Chromium or Oxygen to GaAs to give the semi insulating. This is an important feature required in GaAs technology, since the SI GaAs can be used as a substrate. These elements create deep levels in the forbidden band close to mid gap; which compensate unwanted free carriers or decrease the effective shallow levels leading to an increase in the resistance to the order of $10^8 \Omega cm$.

Another example in GaAs prepared in a certain way, a deep donor known as EL2 compensate shallow acceptors. Then doping of GaAs is not necessary. The modern fabrication methods try to ensure that these native donors (EL2) are present in large enough density in order to fully compensate the shallower defect levels resulting from growth.

For a doped or undoped GaAs; the presence of EL2, or deep acceptor chromium, makes the Fermi level pinned at mid gap and any surplus in concentration of deep level strengthen only the pinning of the Fermi level which makes GaAs semi-insulating.

2.2 Deep levels and their interaction with carriers

Since deep levels act as carrier trapping or as generation-recombination (g-r) centers; depending on their location in the band gap and the capture cross section for electrons and holes.

The impurities whose energies lie near the middle of the band gap act as g-r centers; whereas those nearer the band edges act as traps. Miller et al [13] have suggested notations widely used, and are summarized in the diagrams reproduced from their work in Fig 2.1.

In a neutral semiconductor; the centers are described in terms of the capture rates of the two carriers types. To be an electron trap the rate of capture of electrons at the trap must be greater than the rate of capture of holes, and the converse is applies. If the capture rates are comparable, then the trap function as a recombination center. Sah [14] expresses this functionality in terms of the capture fluences $v_{thn}\sigma_n$ and $v_{thp}\sigma_p$, essentially the fractional capture rate of the two charge carrier populations. If $v_{thn}\sigma_n \cong v_{thp}\sigma_p$ then the defect is referred to as a recombination center, otherwise it is a trap of the appropriate carrier.

In a depletion region the electron and hole density tend to zero, and the thermal emission phenomena dominate; therefore it is not relevant to describe traps in term of their capture process. Instead, the deep levels are defined by electron-hole emission rate, if the emission rates for holes and electrons are comparable, the defect is generation center, thermally producing electron-hole pairs.

Other common nomenclature describes majority and minority traps, referring to the majority and minority charge carriers. Also, electron traps are sometimes referred to as donor traps and hole traps as acceptor traps.

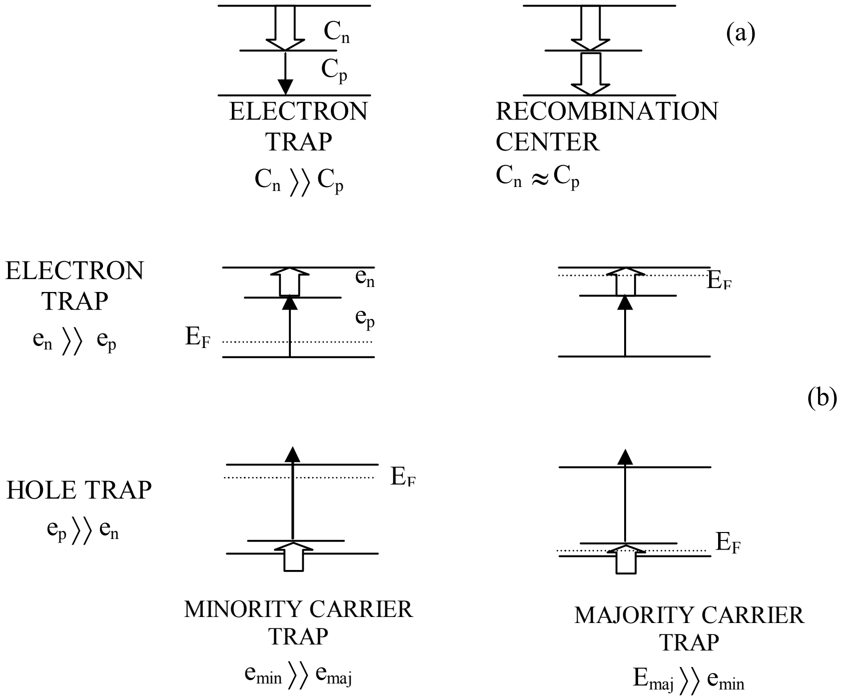

Fig 2.1: **(a)** Definition of the terms « electron trap» and «recombination center» by means of the relative values of the magnitudes of the capture coefficients, indicated by the widths of the arrows. **(b)** Definition of the terms « majority carrier trap» and «minority carrier trap» and «electron» and «holes trap» in the same manner. E_F is the appropriate Fermi level, c, e refer to capture and emission processes and n, p refer to electrons and holes. Suffixes maj, min refer to majority and minority carriers. Reproduced from [13].

2.3 Generation recombination processes

Generation-recombination (g-r) phenomena may take place in one step known as direct g-r or in two steps called indirect g-r. The theory of this has been established by Shockley and Read [15]and Hall [16]. Therefore the mechanism is most frequently termed 'Shockley-Read-Hall (SRH) generation-recombination process'.

The steady state recombination rate of electron-hole pairs in terms of the concentration of the two type of carriers is given by SRH;

$$U_{SRH}(n,p) = \frac{v_{thn} v_{thp} \sigma_n \sigma_p N_T (pn - n_i^2)}{v_{thn} \sigma_n (n + n_1) + v_{thn} \sigma_p (p + p_1)} \qquad 2.1$$

where σ_p and σ_n are the hole and the capture cross sections; v_{thn} and v_{thp} are the electron and hole velocities respectively equal to $\left(\frac{3KT}{m_n^*}\right)^{1/2}$; $\left(\frac{3KT}{m_p^*}\right)^{1/2}$. N_T is the density of g-r centers, n_i is the intrinsic carrier density; n_1 and p_1 are the concentrations of the charge carriers trapped given by

$$n_1 = n_i \exp\left[\left(E_T - E_F\right)/K_B T\right] \qquad 2.2$$

$$P_1 = n_i \exp\left[\left(E_F - E_T\right)/K_B T\right] \qquad 2.3$$

where E_F and E_T are the positions of the Fermi level and of the trap respectively.

The recombination and generation process through g-r center can be described by four transition processes by which carriers interact with defect, electron capture (r_1); electron emission (r_2) and holes capture (r_3); hole emission (r_4). Figure 2.2 summarized this processes.

Process (1) is the capture of an electron from the conduction band by the center; which is assumed to be capable to containing only a single electron. The energy given up by the electron in this process is typically released as a single photon or lattice phonon. The rate of electron capture is then dependent on the free carrier concentration and on the concentration of unoccupied traps ($N_T(1-f)$). Therefore the rate of capture of an electron (r_1) is given by

$$r_1 = \sigma_n v_{thn} n \cdot N_T \cdot (1 - f) \qquad 2.4$$

and the electron emission rate

$$r_2 = e_n \cdot N_T f \qquad 2.5$$

where e_n is the emission probability given by

$$e_n = v_{thn} \sigma_n n_i \exp(\ E_T - E_i / K_B T) \qquad 2.6$$

Similar expression can be obtained for the two other processes, the hole capture

$$r_3 = v_{thp} \cdot \sigma_p N_T \cdot f \qquad 2.7$$

and hole emission rate

$$r_4 = e_p N_T f \qquad 2.8$$

where

$$e_P = v_{thp} \sigma_p n_i \exp(\ E_i - E_T / K_B T) \qquad 2.9$$

the quantities $v_{thn} \sigma_n$ and $v_{thp} \sigma_p$ are known as capture coefficient for electron C_n and hole C_p.

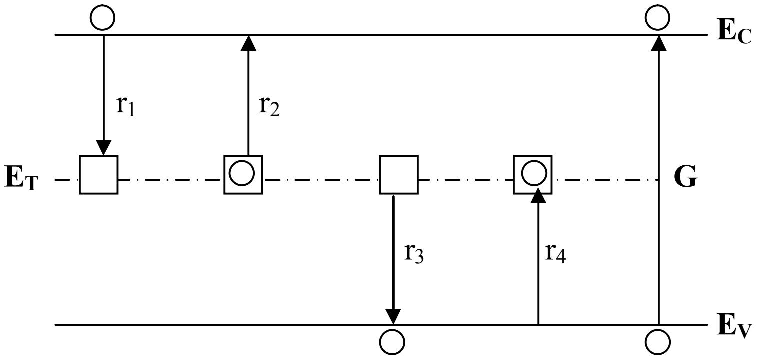

Fig 2.2: Direct transition (G) and indirect (r_i) processes via a single trap level. Reproduced from [14]

Where *f* is the occupation factor of the center given the SRH model as

$$f(n,p)=\frac{v_{thn}\sigma_n n_1+v_{thp}\sigma_p p_1}{v_{thn}\sigma_n(n+n_1)+v_{thp}\sigma_p(p+p_1)} \quad 2.10$$

which under equilibrium conditions, $n_1=n$ and $p_1=p$,therefore the equation can be simplified to the Fermi-Dirac occupation probability

$$f=\frac{1}{1+\exp\left(E_T-E_F/K_BT\right)} \quad 2.11$$

Where E_T is the effective trap energy level.

2.4 Transient evolution of trapped carriers

Because the change of number of electrons trapped in the discreet level is mainly due to four transient processes; thus The rate change of electron concentration in the conduction band because of electron emission and capture processes;

$$-\frac{dn}{dt}=r_1-r_2 \quad 2.12$$

$$-\frac{dn}{dt}=c_n\cdot n\cdot N_T(1-f)-e_nN_T\cdot f \quad 2.13$$

The similar for the rate change of holes concentration in valence band due to holes emission and capture processes;

$$-\frac{dp}{dt}=c_p\cdot p\cdot N_T\cdot f-e_pN_T\cdot(1-f) \quad 2.14$$

As result of these transitions; the rate of change of traps occupied by electron is defined as

$$\frac{dn_t}{dt}=c_n\cdot n\cdot N_T\cdot(1-f)-e_n\cdot N_T\cdot f+e_p N_T\cdot(1-f)-c_p\cdot p\cdot N_T\cdot f \qquad 2.15$$

where $f=\frac{n_t}{N_T}$, and n_t is the density of trapped electron; hence the equation (2.15) is rewritten as follow :

$$\frac{dn_t}{dt}=(e_p+c_n\cdot n)N_T-n_t\cdot(e_p+e_n+c_p p+c_n n) \qquad 2.16$$

$$\frac{dn_t}{n_t+c_2\cdot N_T}=-(e_p+e_n+c_p p+c_n n)dt \qquad 2.17$$

where

$$c_2=\frac{c_n n+e_p}{e_p+e_n+c_n n+c_p p} \qquad 2.18$$

The solution of eq (2.17) given by Philips and Lowney (1983)[31] is:

$$n_t(t)=c_3\exp\left\{-\frac{t}{\tau}\right\}+c_4 \qquad 2.19$$

where τ is the time constant defined by

$$\tau=\frac{1}{e_p+e_n+c_p p+c_n n} \qquad 2.20$$

the constants c_3 and c_4 are determined from the limiting condition in the occupancy of the trap as follow:

$n_t=n_{ti}$ at $t=0$ therefore $c_3+c_4=n_{ti}$

$n_t=n_{tf}$ at $t\rightarrow\infty$ therefore $c_4=n_{tf}$

hence the equation (2.19)is rewritten as :

$$n_t(t)=(n_{ti}-n_{tf})e^{-t/\tau}+n_{tf} \qquad 2.21$$

where the subscripts (*i*) and (*f*) denote the initial and final trap occupancies.

-In the case where the trap is electron trap; the time constant reduced to

$$\tau=\frac{1}{c_n n+e_n} \qquad 2.22$$

if it is initially full; $n_{ti}=N_T$ and $n_{tf}=0$ hence:

$$n_t(t)=N_T\cdot e^{-t/\tau} \qquad 2.23$$

the ionized electron trap density N_T^+ is given by

$$N_T^+ = N_T - n_t(t) \qquad 2.24$$

$$N_T^+ = N_T\{1 - e^{-t/\tau}\} \qquad 2.25$$

This case refers to emission in depletion region.

-But if the trap is initially empty $n_{ti} = 0$ and $n_{tf} = N_T$, therefore

$$n_t(t) = N_T\{1 - e^{-t/\tau}\} \qquad 2.26$$

and the density of the ionized electron from this trap is :

$$N_T^+(t) = N_T \cdot e^{-t/\tau} \qquad 2.27$$

This case refers to capture in the neutral region of semiconductor; hence $c_n n >> e_n$ and the time constant may be reduced to

$$\tau = \frac{1}{c_n \cdot n} \qquad 2.28$$

2.5 Detailed balance principle

The carrier capture rates of traps are linked to the thermal emission rates via the Detailed balance principle. This Principle states that the net rate is zero in equilibrium. That is the net capture and emission are equal. hence $dn_t/dt = 0$ and for electron trap ($e_p, c_p \langle\langle\, e_n, c_n$), the emission rate may given by

$$e_n = c_n \cdot n \frac{1-f}{f} \qquad 2.29$$

If n is expressed as $n = N_c \exp\left(\frac{E_F - E_C}{K_B T}\right)$, and N_C, E_C are the effective density of state in the conduction band and its minimal edge and Substituted in eq (2.29) and using the expression for f from 2.11 and expressing in terms of capture we obtain

$$e_n = v_{thn}\, \sigma_n N_C \exp\left(-\frac{E_C - E_T}{K_B T}\right) \qquad 2.30$$

σ_n is the capture cross section where it is quite common to use its concept instead of the meaningful physical quantity of the capture coefficient c_n [37], it is defined as

$$\sigma_n = \frac{c_n}{\langle v \rangle} \qquad 2.31$$

where $\langle v \rangle$ is the average thermal velocity of electrons.

And because we have $v_{thn} \propto \sqrt{T}$ and $N_C \propto \sqrt{T^3}$, we can obtain the following expression;

$$e_n = \gamma_n \sigma_n T^2 \exp\left(-\frac{E_C - E_T}{K_B T}\right) \quad 2.32$$

where γ_n is a material dependent constant independent of temperature. A similar expression can be given for hole traps, taking the appropriate terms of parameters to such traps.

$$e_p = \gamma_p \sigma_p T^2 \exp\left(-\frac{E_T - E_V}{K_B T}\right) \quad 2.33$$

The γ parameters are well know for GaAs, at around 2.28×10^{20} $cm^{-2}s^{-1}K^{-2}$for electron traps [20] and $1.7\times10^{21}cm^{-2}s^{-1}K^{-2}$ for hole traps [19].

2.6 Deep Level Transient Spectroscopy (DLTS) technique

It is important to characterize accurately the deep levels in order to establish their origin; their spatial positions and concentrations; their effect on device performance and ways of minimizing their detrimental effects or even attempting to eliminate some of them altogether.

Therefore evaluation of activation energies, apparent capture cross sections and their density, which together provide a signature for each trap in the material; lead to systematic study of trapping levels. In most situations the deep centers are present in concentrations many magnitudes smaller than the concentration of shallow states. This may require sensitive measurement techniques.

The standard technique used is based upon the observation of transients; which are associated with the carrier capture and emission processes at the deep state centers only in space charge (depletion) region of p-n junctions and Schottky barriers[3]; the time constant of the transient provides information about the rates of these processes and transient amplitude reveals information about the deep states concentration. The most widely used transient method is Deep Level Transient Spectroscopy (DLTS) technique which was first developed by Lang in 1974 [22]. It has gained wide spread use due to the many advantages over other methods in that it is;

1/ rapid; the DLTS spectrum produced contains a series of isolated peaks; each corresponding to an individual trap, hence; the presence or the absence of a particular trap can be determined very quickly.

2/ capable of much greater sensitivity and of evaluating all the trap parameters (activation energy; capture cross section; concentration and profile).

3/ the data is easy be interpreted (capable to distinguishing between majority and minority traps)

4/ used to observe a greater range of trap (since the admittance spectroscopy is only limited to majority traps and frequently best suited to shallow states with decreasing sensitivity with depth into the band gap).

An example of DLTS spectrum is presented for illustrative purposes in figure 2.3.

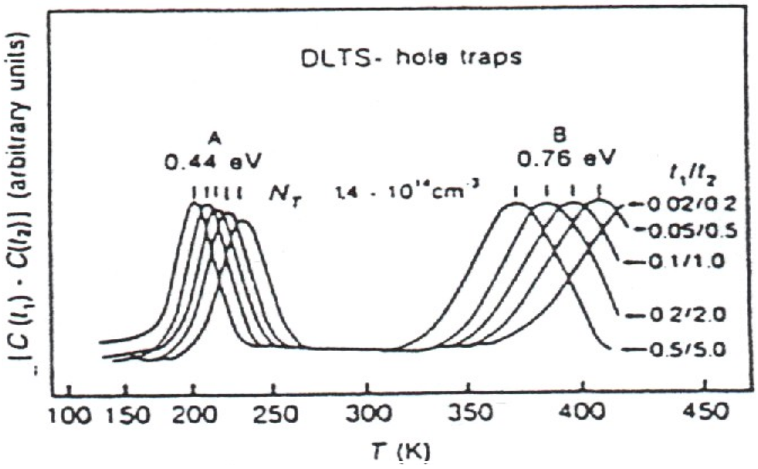

Fig 2.3 : DLTS spectrum of different rate windows After [22]

2.6.1 Principle of the technique

As its name suggest, DLTS utilizes transient techniques. Following a bias change; the space charge region edge moves. The free carriers flow rapidly in or out of the region. This results in a rapid change in the position of the Fermi level; to reach a new equilibrium. The traps fill rapidly, by capture, or empty slowly, by emission.

A reverse bias is applied to a Schottky barrier or PN junction, resulting in a wider depletion region, where the band bending occurs and may raise the energy level of the trap will above the Fermi level. Hence the trap becomes essentially empty. As the band structure lowers towards the depletion region edge and becomes the band structure of uncharged material; the trap level may fall bellow the Fermi level. Hence the traps outside the depletion region are essentially filled. However, any trap lying between the junction and the point where it crosses the Fermi level will essentially empty by thermal emission and those bellow the Fermi level are full.

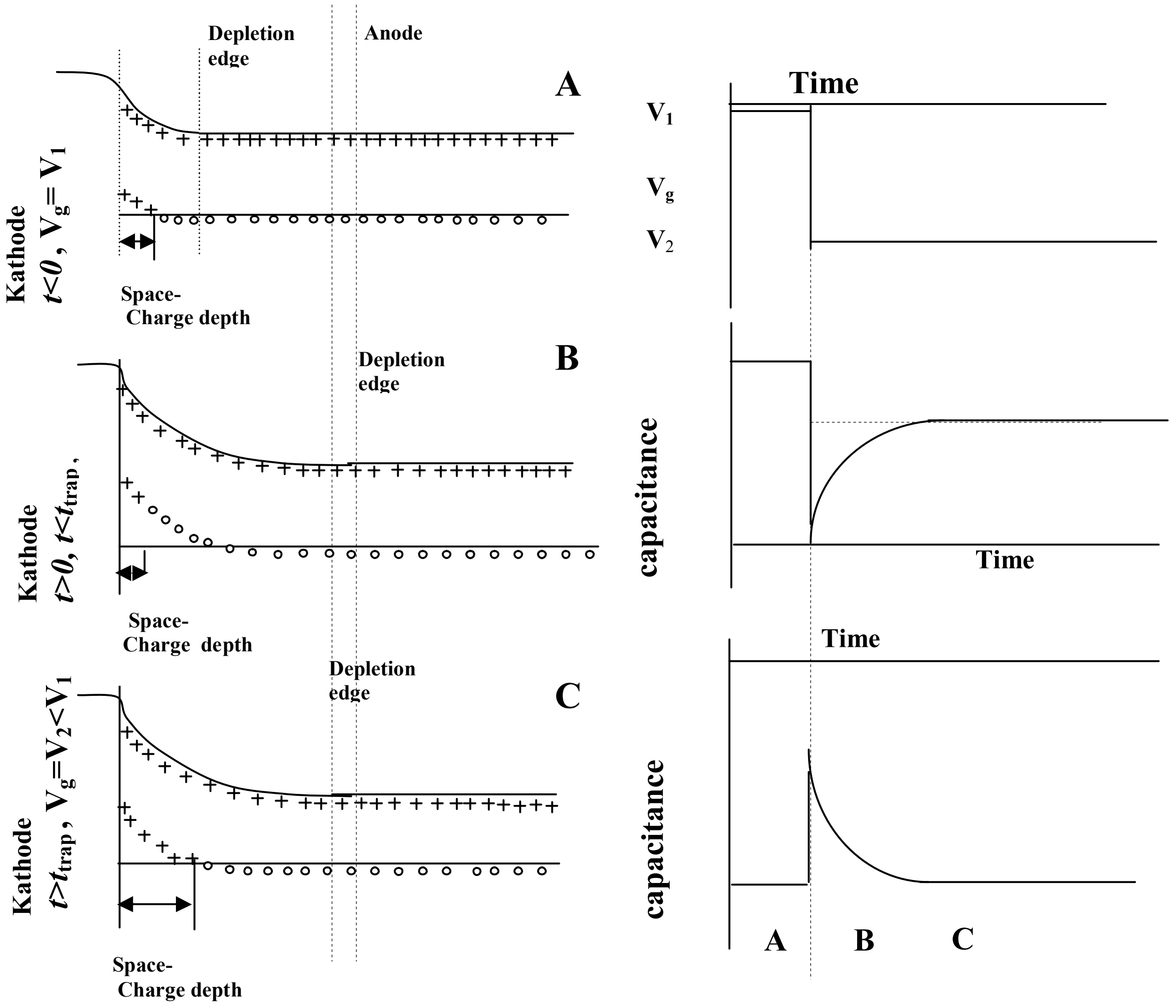

Fig 2.4 : Band diagrams (left) showing the effect of an abrupt gate voltage change on the population of a single midgap trap, and the knock-on effect on the depletion depth. Capacitance (right) showing the response to the reverse voltage change and transient response due to the trap.

The extent of depletion region depends directly on the contents of the space charge, thereby any change in the traps occupancy will affect this extent. Since the time of emission-capture carriers and reaching equilibrium is non-zero, then the depletion region will vary in size over this time. Hence the parameter measured is the capacitance of this depletion region. If the trap is active into a probed region with an observable time constant; a transient will be observed in the capacitance measurement as the depletion thickness change to its equilibrium value. From eq (2.32), the rate at which the trap reaches equilibrium is strongly temperature dependent; the observed transient will also be temperature dependent. This transient are measured by the well known ‘rate window’ technique, by sampling at two points with time delays of t_1 and t_2 and the difference recorded. As the temperature increases the transient change in manner characteristic of a particular trap. Peaks appears in the spectrum when the emission rate carriers from the trap correspond to the rate window $e_{\max}$ set by the chosen values of t_1 and

t_2. Figure 2.5 illustrates the case of the single component transient, where the time constant is the same as the rate window in the middle of temperature range; at low temperature owing to the ionization which occur to an small fraction of trap; the transient difference between t_1 and t_2 is small (which mean that time constant is orders of magnitude longer than the rate window). At high temperatures; the emission rate of trap (trap time constant) is shorter due the transient difference which is also small since the trap is completely ionized .

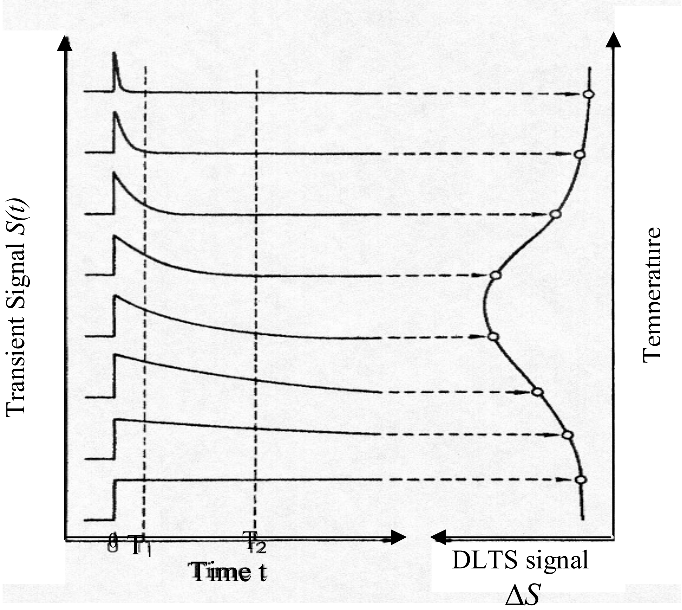

Fig 2.5: The formation of a DLTS spectrum (right) from a series of transients at different temperatures (left). The DLTS signal at a given temperature is transient signal at time T_1 minus the transient signal at time T_2. when the transient time constant becomes similar to the time constant of the rate window, a peak is produced. Reproduced from [22].

The variation in the peak position- hence Time constant-with temperature can be used to evaluated the trap parameters. From the dependence of the emission rate on temperature one can get the activation energy, the capture cross section and from the DLTS peak , the density of the trap can be determined.

The modulation of the measured quantity is entirely due to a variation in the width of depletion region in time, which in an n-type semiconductor is given by

$$W(t)=\sqrt{\frac{2\cdot\varepsilon\varepsilon_s(V_{Bi}-V_G)}{q\cdot(N_D+N_T^+(t))}} \qquad 2.34$$

N_D and $N_T^+(t)$ are the doping density and the ionized electron traps respectively.

The normalizes capacitance transient is defined by the expression

$$S(t)=\frac{C(t)-C(\infty)}{C(\infty)} \qquad 2.35$$

and because $C(t)$ is inversely proportional to $W(t)$, then

$$S(t)=\frac{\frac{1}{W(t)}-\frac{1}{W(\infty)}}{\frac{1}{W(\infty)}} \qquad 2.36$$

$$=\frac{W(\infty)}{W(t)}-1 \qquad 2.37$$

By substituting the expressions of $W(t)$ and $W(\infty)$, we obtain

$$S(t)=\frac{\sqrt{1+\frac{N_T^+(t)}{N_D}}}{\sqrt{1+\frac{N_T}{N_D}}}-1 \qquad 2.38$$

using the equation (2.25), the equation (2.38) can be rewritten as

$$S(t)=\frac{\sqrt{1+\frac{N_T}{N_D}\left(1-\exp\left(-{t}/{\tau}\right)\right)}}{\sqrt{1+\frac{N_T}{N_D}}}-1 \qquad 2.39$$

if $N_T\langle N_D$; this expression is reduced to

$$S(t)\approx S_0\exp\left(\frac{-t}{\tau}\right) \qquad 2.40$$

where S_0 represent the normalized transient amplitude equal to $-\frac{N_T}{2\cdot N_D}$; hence the concentration of the trap is extracted from

$$N_T=2\cdot N_D|S_0| \qquad 2.41$$

DLTS is also useful since there is a direct relation between the rate window(t_1, t_2) and the transient time constant. This can be derived from the fact that the single is at its maximum (peak) at the rate window, hence its derivative equal to zero

$$\frac{d}{d\tau}(S(t_2)-S(t_1))=S_0\left[\frac{t_2}{\tau^2}\exp\left(-\frac{t_2}{\tau}\right)-\frac{t_1}{\tau^2}\exp\left(-\frac{t_1}{\tau}\right)\right]=0 \qquad 2.42$$

Since $\frac{1}{\tau^2}$ is deferent of zero then

$$t_2\exp\frac{-t_2}{\tau}=t_1\exp\frac{-t_1}{\tau} \qquad 2.43$$

hence

$$\frac{t_2}{t_1}=\exp\left(\frac{t_2-t_1}{\tau}\right) \qquad 2.44$$

then the transient time is given by

$$\tau=\frac{t_2-t_1}{\log\left(\frac{t_2}{t_1}\right)} \qquad 2.45$$

and if the ration t_2/t_1 is maintained constant at some value r throughout the variation of rate window .

$$\tau=\tau_{\max}=\frac{r-1}{\log r}t_1 \qquad 2.46$$

and the emission rate is then calculate simply by taking the reciprocal of this time constant as

$$e_n=\frac{1}{\tau} \qquad 2.47$$

If an Arrhenius plot is produced from $\log\left(e_n/T^2\right)$ against $1/T$ gives a straight line whose slope is proportional to the activation energy of the traps and the intersection at $1/T=0$ with the $\log\left(e_n/T^2\right)$ axis is proportional to the capture cross section. Figure 2.6 illustrate this step.

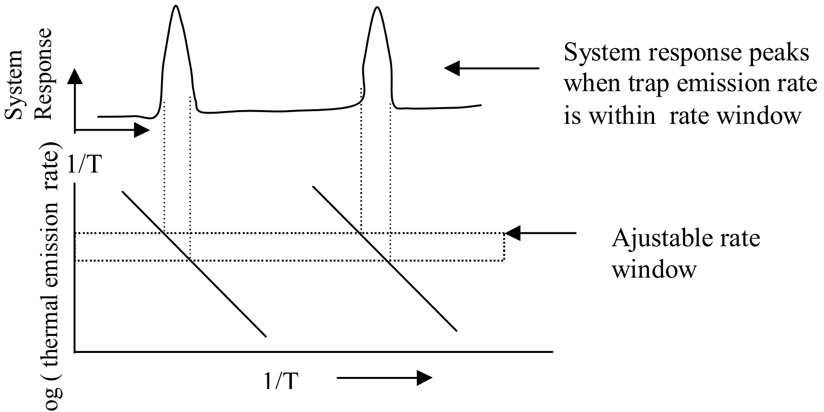

Fig 2.6: Basic idea of the rate window

2.7 Traps in GaAs FET and Backgating

There are three specific regions of the devices where the traps can be located in GaAs FETs[42];

- At the surface of the ungated regions of the device.
- In the active layer
- Near the channel-substrate interface or in the substrate itself

Figure 2 .7 illustrated these three regions. When they are located in substrate, they might be responsible of an interesting parasitic effect which is the backgating (or sidegating) phenomenon. Due to a negative voltage pulse applied directly to the substrate or voltage in neighboring devices in the same integrated circuit. This effect caused a device current reduction [38.39.40.41].

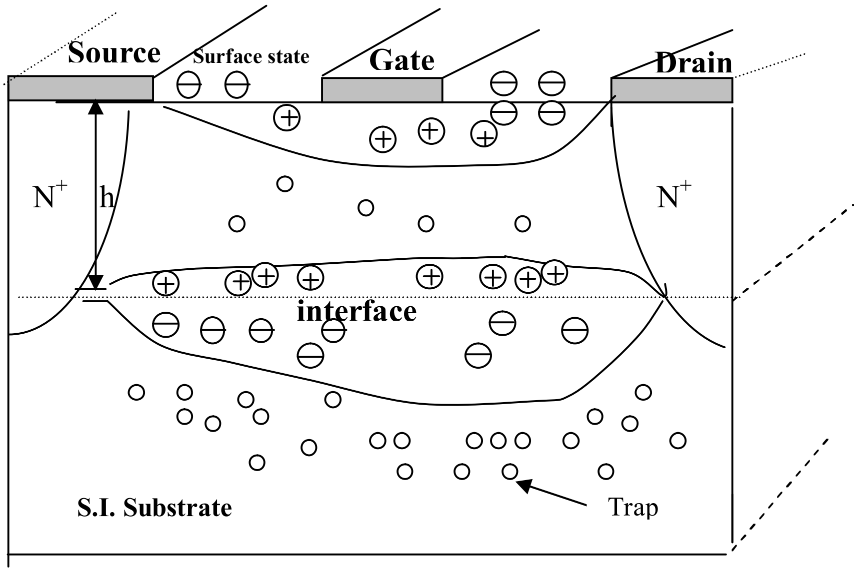

Fig 2.7: Diagram to show the location of the traps within the device geometry.

when an negative voltage is applied, it can fall the potential at the interface to being proportional to $V_{Bi}-V_G$; and due to the traps in the substrate side of channel-substrate interface. Then change in device total conductance $\Delta\cdot G_{DS}$ expressed by [44];

$$\Delta\cdot G_{DS}=C\cdot\Delta a \qquad 2.48$$

where C is constant; and Δa is the change in the channel width due to the channel-substrate interface which increase when the depletion width decrease; therefore as generally; assuming that $N_T \langle\langle N_D$; the thickness of the depletion region is defined by;

$$a_b \approx \sqrt{\frac{2\cdot\varepsilon_s\cdot V_{eff}}{q\cdot N_{Deff}}} \qquad 2.49$$

where V_{eff} is the voltage drop in the space charge region at the channel-substrate interface and N_{Deff} is the effective donor density which is in time dependent because of the deep states.

2.8 Backgating effect

Among of many parasitic effects due to the presence of defects within the substrate is the backgating effect (or sidegating effect). It is caused by the formation of space charge region at the channel-substrate junction owing to an applied negative bias to the substrate. Generally there is a threshold voltage associated with the backgating effect which means that channel conductance is reduced only when the negative voltage applied to the semi insulator substrate exceed a certain value. But it was observed that this condition may not always happen (backgating without threshold voltage). Previous works confirmed that the threshold voltage for sudden increase in substrate leakage current is exactly the same as the threshold voltage for the backgating effect [23]. This correlation shows that this effect depends not only on the properties of channel-substrate junction but also on the current transport through the substrate.

To explain the phenomena, several models have been proposed. When the channel current start to decrease when the negative voltage of substrate exceeds a certain tension; it is attributed to the widening of depletion region of the channel substrate interface. According to the model proposed by Lee et al [23] by measuring the drain and substrate current as function of the substrate voltage; it was shown that the channel current (conductance) reduction coincide with the sharp increase in substrate current at a certain point defined as threshold voltage. Several different regions are observed in *(I*, *V)* characteristic.

Before threshold voltage the *(I-V)* characteristic is ohmic and the substrate maintains high resistance like a good insulator and the applied voltage drops mainly across the substrate with only little voltage across the junction and therefore the channel current is slightly affected. After this; a sudden increase of the current attributed to the space charge limited current SCLC where $I \alpha V^{\alpha}, (\alpha \rangle 1)$. Lampert[24] suggests that the threshold voltage is no other than the trap filled limit voltage. Before threshold, empty traps are filled by the injected electron and the current is low. Above that the injected electrons cause the substrate to become sufficiently conducting to transfer a sizeable part of the applied voltage to the channel-substrate interface, the current rises steeply and the *(I-V)* characteristic start to follow an injected carriers controlled power law SCL current. However, it was noted that the threshold voltage is very different from what is expected.

For the second type of backgating(without threshold), the outdiffusion of impurities from the substrate causes a sudden decrease of channel current immediately after application of a negative bias [33, 19]. The space charge region localized at the channel-substrate interface is due to the ionization of hole traps resulting in to an excess of negative charge within the substrate which needs to be compensated by a positive charges of side of channel which is accomplished at the expense of depleting electrons and thereby restricting the effective channel width[1].

2.8.1 Backgating effects in GaAs FETs

There are so many effects related to backgating so that it is considered as the most serious problem in discrete devices as well as integrated circuits [43.45]. Most of low frequency anomalies [47], light induced effects [48], low frequency oscillations and g-r noise [49] and most of the drift phenomenon [50] are, to mention a few, related to traps near the channel-substrate interface which causes backgating [46].

2.8.2 Reduction of backgating

A lot of effort has been devoted for the elimination of backgating or at least reducing it. In the early days, a high purity epitaxially grown buffer layer achieved some success in reducing backgating [51, 52, 53]. However this buffer layer did not eliminate the problem as it may itself contain deep traps [54]. Backgating was also reported to be reduced by proton [17] and oxygen [18] implantation in the SI substrate. A p-type layer buried under the channel also reduced backgating and improved the device characteristics [55]. But it seems that the most effective way, up to now, in reducing the backgating related effects is the growth of a buffer layer by MBE at low substrate temperatures [56, 57].

2.9 Life time and relaxation semiconductors

The concept of relaxation semiconductor and some of the corresponding transport relations was first introduced by Van Roosbroeck and co-work [25], they suggested that materials in which the dielectric relaxation time $\tau_D = \rho\varepsilon\varepsilon_0$ (where ρ is the resistivity of the material, ε is the relative dielectric constant of material, and ε_0 is the permittivity of free space) exceeded the carrier recombination lifetime τ_0, exhibited a new regime of semiconductor behavior. The opposite case, $\tau_0 \rangle\rangle \tau_D$, was called the lifetime regime, and it encompasses most of the more common semiconductor materials and applications. Fundamentally different forms of transport behavior were predicted for semiconductors in the relaxation regime, a regime in which space charge plays a major role [29].

The relaxation limit is reached in materials with a high resistivity due to low carrier density and in those which have a fast electron-hole pairs generation-recombination rate due to a high density of generation-recombination (g-r) centers. Thus poor quality silicon devices containing g-r centers may become relaxationlike at low temperature where the free carriers freeze out. Semi-insulating compound semiconductors such as GaAs are very good candidates for the relaxation regime. The typical resistivity of GaAs is of the order of $10^8 \Omega cm$ yielding a dielectric relaxation time of $\sim 10^{-4} s$, while recombination lifetimes (τ_0) are estimated to be near or below $10^{-8} s$. This short generation-recombination lifetime relative to the dielectric relaxation time means that, if the material is disturbed from its neutral state, the excess carriers have recombined long before neutrality can be restored by the flow of charge. In the lifetime case neutrality is restored before the excess carriers recombine, by the flow of charge driven by the electric field but limited by the resistivity. In the relaxation case there are many generation recombination centers that produce the short lifetime and hence local carrier equilibrium so that there is no far-reaching external influence. The main differences between lifetime and relaxation materials have been given by Quiesser [6]in table 2.1.

	Relaxation case (High resistivity materials)	Lifetime case (Conventional semiconductors)
Recombination lifetime	$\tau_0 \cong 10^{-8} s$	$\tau_0 \cong 10^{-3} s$
Dielectric relaxation time	$\tau_D \cong 10^{-4} s$ (compensated GaAs)	$\tau_D \cong 10^{-12} s$ (Ge)
Resistivity	$10^8 \Omega cm$	$1 \Omega cm$
Candidates Materials	Amorphous and compensated materials, "insulators", conventional semiconductors at low temperature	Typical doped semiconductors (Ge,Si) at room temperature
Predominance effects	Space charge effects	Charge neutrality
	Recombination after a few mean free paths	Extended diffusion lengths
	Recombinative injection	Injection reduces the resistance
Fermi level	A simple quasi Fermi level	Separate quasi Fermi levels for the two types of carriers
propagation of the pulse	Pulse drifts like majorities	Pulse drifts like minorities
	Local equilibrium, like intrinsic material	Externally controllable electron holes density product
Device behavior	Governed by macroscopic features: space charge, relaxation-time.	predictable from microscopic properties of carriers dopants

Table 2.1: The main differences between lifetime and relaxation materials.

2.9.1 Characteristics of relaxation material

In the practical cases there are so many g-r centers that they will control the short lifetime and determine the carrier equilibrium locally and no longer permit far-reaching external influences. This essential result is expressed by the deceptively simple formula [5,6].

$$np=n_i^2\neq f(V) \tag{2.50}$$

which means that the product of mobile carrier densities is no longer depend on bias, as was the case for the lifetime material where $np=n_i^2\exp(qV/K_BT)=f(V)$, it means that there is no longer the possibility of establishing two separated quasi-Fermi levels. Instead the two quasi Fermi levels are now locally equalized given as

$$\phi_n=\phi_p=\phi_R \tag{2.51}$$

where ϕ_R is the relaxation potential [29]. It determines the concentrations of mobile as well trapped charges just as does the familiar Fermi potential at equilibrium, and ϕ_n and ϕ_p are the separated quasi Fermi levels for electrons and holes respectively. An important fact given by relaxation case semiconductor is to have tendency towards zero net recombination rate for the steady state equilibrium rather than towards zero space charge, as does the lifetime case material.

The equation 2.50 has some and surprising consequences. Firstly the injection of minority carriers can lead to an increase in resistivity, opposite to the customary resistivity decrease of life time materials. For example, we consider an n-type relaxation case material with equilibrium electron density n_0, minority hole density $p_0\langle n_0$. When we inject holes δp, the response δn for the majority carriers is obtained by:

We must have local equilibrium again after some transient behaviors, thus

$$(n_0+\delta n)(p_0+\delta p)=n_i^2 \tag{2.52}$$

since $n_0p_0=n_i^2$, one gets

$$n_0\delta p+p_0\delta n+\delta n\,\delta p=0 \tag{2.53}$$

from which follows

$$\delta n=-n_0\delta p(\delta p+p_0)^{-1} \tag{2.54}$$

with the condition $\delta p\rangle p_0$ one obtains the remarkable result

$$\delta n \rightarrow -n_0 \quad 2.55$$

which means essentially all previously mobile carriers have disappeared after the injection; obviously this leads to a resistivity increase.

The condition $\delta p \rangle p_0$ is easily fulfilled, since p_0 can be made small by the original doping; this holds for the case of little carrier-trapping, with trapping, the required amount of charge to be injected becomes larger [29]. This type of injection is characteristic for the relaxation-case, it is called 'recombinative space charge injection'. This mechanism is responsible for the typical sublinear voltage dependence of currents often found in relaxation-case materials, because an increase in voltage enlarges a high-resistance space charge region, thus increasing differential resistance and leading to sublinear behavior, sometimes even negative resistances. This effect of recombinative injection is particularly pronounced when the less mobile carriers are injected into relatively high-conductance materials [21].

Relaxation-case injection differs from injection into lifetime-case materials in another general aspect. The potential disturbance created by an injected pulse of carriers drifts when an electric field is applied. In the relaxation case the disturbance moves in the same direction as the majority carriers. While the concentration change of majorities is drastic as shown by equation (2.55), the minorities are only slightly affected. In essence the minorities are quickly depleted by recombination while majority–carrier disturbances are stable against neutralization, which is typical consequence of $\frac{\tau_0}{\tau_D} \langle\langle 1$. In the lifetime the situation is exactly opposite.

The next consequence of the constraint $np=n_i^2$ concerns the concept of maximal resistivity $\rho_{\max}$. The maximum possible resistivity becomes a meaningful and significant quantity for the relaxation case. $\rho_{\max}$ is attained when both types of carriers have a density ratio equal to the inverse mobility ratio, thus equalizing the drift components:

$$\mu_n n_{\max} = \mu_p p_{\max} \quad 2.56$$

the densities are

$$n_{\max} = \left(\frac{\mu_n}{\mu_p}\right)^{-1/2} n_i \text{ and } p_{\max} = \left(\frac{\mu_n}{\mu_p}\right)^{1/2} n_i \quad 2.57$$

The expression for the maximum resistivity is

$$\rho_{\max}^{-1} = 2qn_i\left(\mu_n\mu_p\right)^{1/2} \quad 2.58$$

Notice that this maximal resistivity does not depend on doping at all but essentially an intrinsic property of the material, as signified by its inverse proportionality to n_i . The temperature dependence is mainly that of n_i , which varies as $\exp\left(-E_g/2K_BT\right)$ [30], since in general the mobilities depend less strongly on temperature.

The regions where $\rho_{\max}$ is reached, relaxation case structures have a tendency to develop it this in turn determine the impedance of structure. First, it is easy to see that a reverse biased to space charge layer tends to approach $\rho_{\max}$. The reverse bias removes carriers from the region and depletes them. If the field were initially to extract one species of carriers preferentially, then this species (holes) contributes less and less to reverse current until equilibrium is attained when the two types contribute equally again.

Second, a region of maximal resistivity also arises in the important case of a forward-biased junction, which may also be realized by injecting contact. This general problem of transport in relaxation material is treated largely by Van Roosbroeck and Casey in [29].

2.9.2 Recombinative pinning

The tendency towards maximal resistivity, which is a doping independent quantity is equivalent to saying that the position of Fermi energy within the forbidden gap is no longer controlled by dopant impurities [6]. Due to the specific recombination behavior in relaxation case, which causes the maximal resistivity hence the Fermi level is shifted closely to intrinsic position , where in the lifetime-case the concept of the pinning of the Fermi level is caused by the impurities with substantial density of states. In relaxation materials this important phenomenon is called recombinative pinning. It is not necessary required many states of centers to fix the Fermi level; knowing that in lifetime we have the costmary conducting doping when in relaxation case the impurities primarily influence the generation-recombination traffic and through it the conductivity. Recombinative pinning makes the material appear similar to the intrinsic case, this intrinsic behavior resembles the usual intrinsic characteristics resulting from the elevated temperatures, generally the generation recombination processes are rapid compared with all other mechanisms, notably influence of dopants or bias therefore the constraint of Eq (2.50) is established locally everywhere. In truly intrinsic semiconductors the rate of thermal activation dominates, when in the relaxation material the larges density of centers and traps are the responsible to established the equilibrium. The fact that the capture cross sections tend to become very large and the space filling which makes τ_0 very small, and the recombinative pinning arises increasing τ_D, the relaxation-case is in part self-realizing. The internal consistency is attained in a closed loop of cause and effect :

large capture cross sections → short lifetimes → relaxation-case condition → large capture.