Chapter 4

RESULTS AND DISCUSSIONS

4.1 Introduction

The aim of this work is to show that the backgating phenomenon is determined by the concentration and type of traps. The backgate to channel spacing is also an important parameter. The substrate current is generally related to backgating and is also related to the above parameters. Since traps are very sensitive to temperature variation, this effect is also studied.

The simulations were made for two types of structures; in each one the substrate contains a shallow level and a deep one as listed in table 4.1. The substrate for the first type initially slightly p-type referred to as np^-. In the second structure referred to as nn^-; the substrate is initially slightly n-type. In both cases the backgating effect and substrate current are studied as function of adding deep acceptors to enhance the shallow acceptors of np^- and compensate the shallow donors of nn^-. Deep donors are also added to study their effects on the backgating and substrate current.

The deep acceptors are assumed to be located at the middle of the energy gap (E_V+ 0.71 eV); this is atypical value for Cr levels in Cr-doped semi insulating GaAs widely used as substrate for GaAs FETs. The deep donors are located at (E_C - 0.74 eV) which is a typical value for the well known EL2 which is a characterization of physical defects in GaAs bulk.

Structure	*Deep level*			*Shallow level*
	Type	$E_T - E_v(eV)$	$N_T(cm^{-3})$	*Type* $N(cm^{-3})$
Substrate 1 (nn^-)	Acceptors and/or donors	variable	parameter	Donors 10^7
Substrate 2 (np^-)	Acceptors and/or donors	variable	parameter	Acceptors 10^7

Table 4.1: The two types of substrates used in the simulation.

The variable parameters which affect the channel conductance and substrate current are summarized as follows:

- different acceptor trap densities.
- different donors trap densities.
- different energy levels for acceptor and donors traps.

- different temperatures.
- different substrate lengths.

4.2 The conductance and substrate current in absence of traps

In the absence of deep levels; the calculated conductance and substrate current for both structures are presented in fig 4.1.

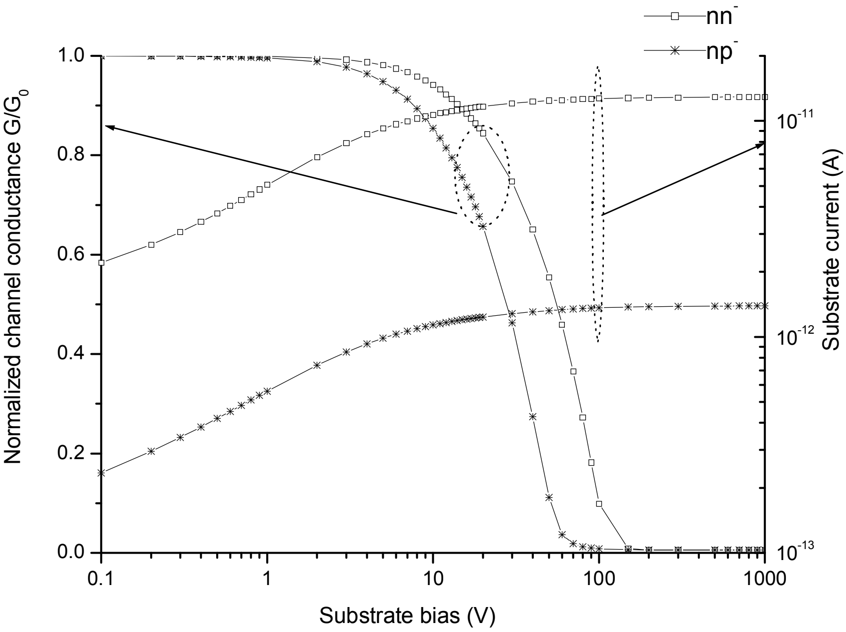


Fig 4.1 : The normalized channel conductance and substrate current as function of substrate voltage for both structures in absence of traps .

We note that the conductance is more affected in the np$^-$ structure. This is because the potential barrier at the channel substrate interface is bigger as shown in fig 4.2.

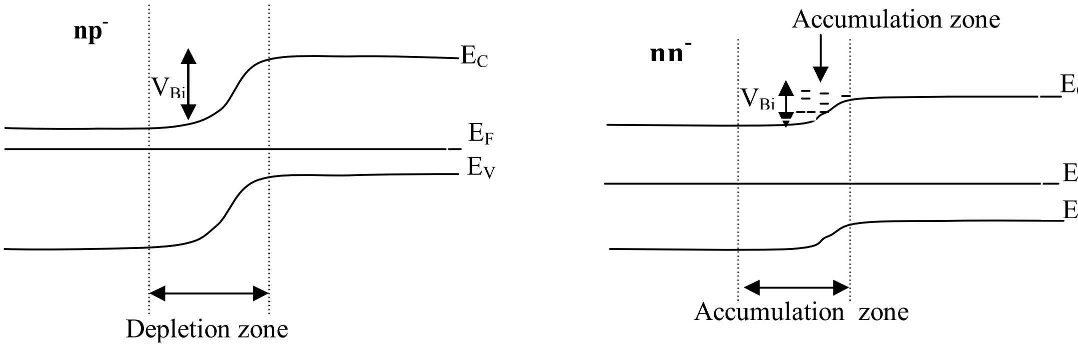


Fig 4.2 : The band bending in the np$^-$ and nn$^-$ structures in equilibrium.

The conductance is initially constant up to 1V in both structures. Then it decreases but more rapidly in the np$^-$ structure. The voltage at which the conductance start to decreases is known as the threshold voltage (V_T). To explain this difference, the electron and hole distribution in channel is presented in figure 4.3 for different voltages.

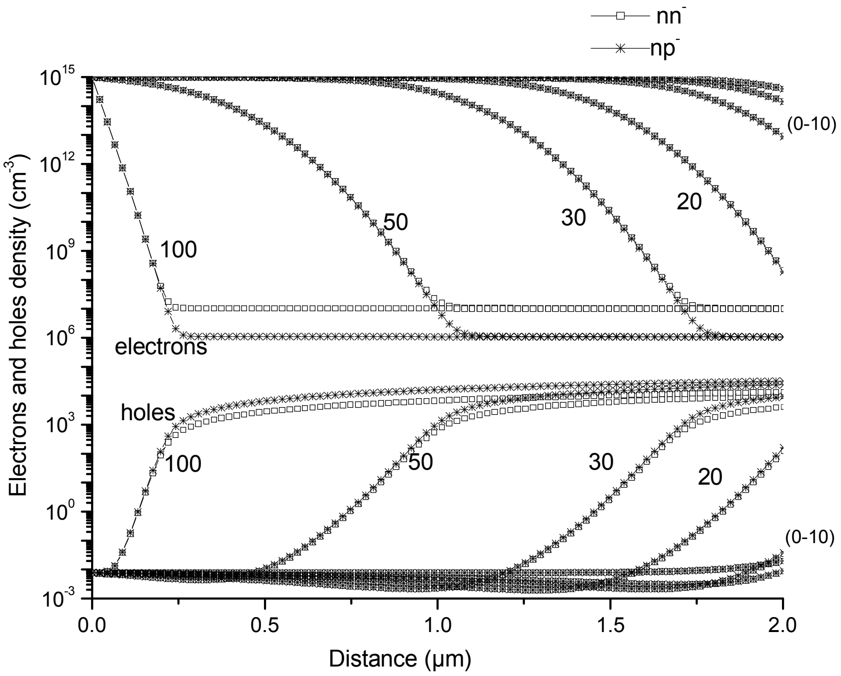


Fig 4.3 : The distribution of electrons and holes in the channel in both structures for different voltages.

The electron density in the nn$^-$ structure decrease to values greater than those of the np$^-$ structure for the same voltage. Hence the conductance of the nn$^-$ structure is bigger than that of np$^-$. We observe also that the density of holes is not much affected before the threshold in both structures. At the threshold, the effect is considerable.

For the substrate current; it is proportional to $V^{1/2}$ before it saturates at about 30 V in both cases. First it is proportional to $V^{1/2}$ because it is a generation type which dominates in GaAs which usually contains very high density of g-r centers. These centers are typical of deep levels located at about midgap but are not charged since they can capture electrons and holes equally.

For the saturation, it can be due to either the saturation of the velocity or the total depletion of the channel. However; the most probable cause is the first. This is justified by the fact that we used electric field dependent mobility. In addition the current in nn$^-$ structure is given by

$$I_{nn^-} = J_n A = \sigma_n E A \qquad 4.1$$

hence $$I_{nn^-} = qn\mu_n E \cdot A \qquad 4.2$$

where A is the area which is $10^{-6}\ cm^{-2}$.

For the np$^-$ structure the current is given by

$$I_{np^-}=qp\mu_p E\cdot A \qquad 4.3$$

Since the field, the density and the area are the same in both structures; then

$$\frac{I_{nn^-}}{I_{np^-}}\approx\frac{\mu_n}{\mu_p}\approx\frac{7300}{425}=17$$

To clarify this more, we have compared the simulated substrate current assuming constant mobility (non saturated velocity) and a field dependent mobility (saturated velocity). These are presented in fig 4.4. It is clear that the current does not saturate in the first case while it tend to saturate in the second.

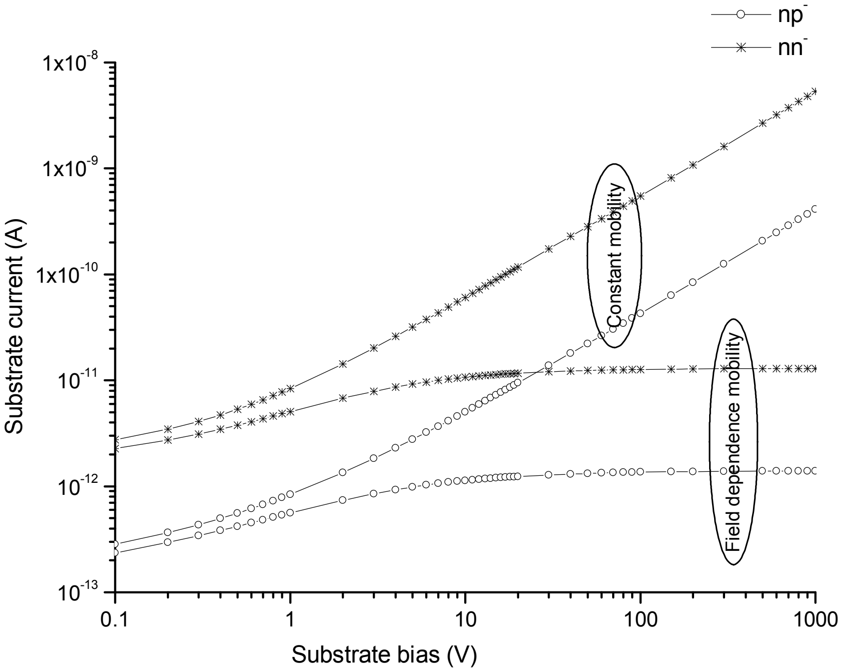


Fig 4.4 : The effect of field dependency of the mobility on the calculated substrate current for the structures np$^-$ and nn$^-$.

4.3 The effect of deep acceptors

Adding deep acceptors located at $E_V+0.71$ *eV* give the results shown in figure 4.5 for the structures nn^- (a) and np^- (b).

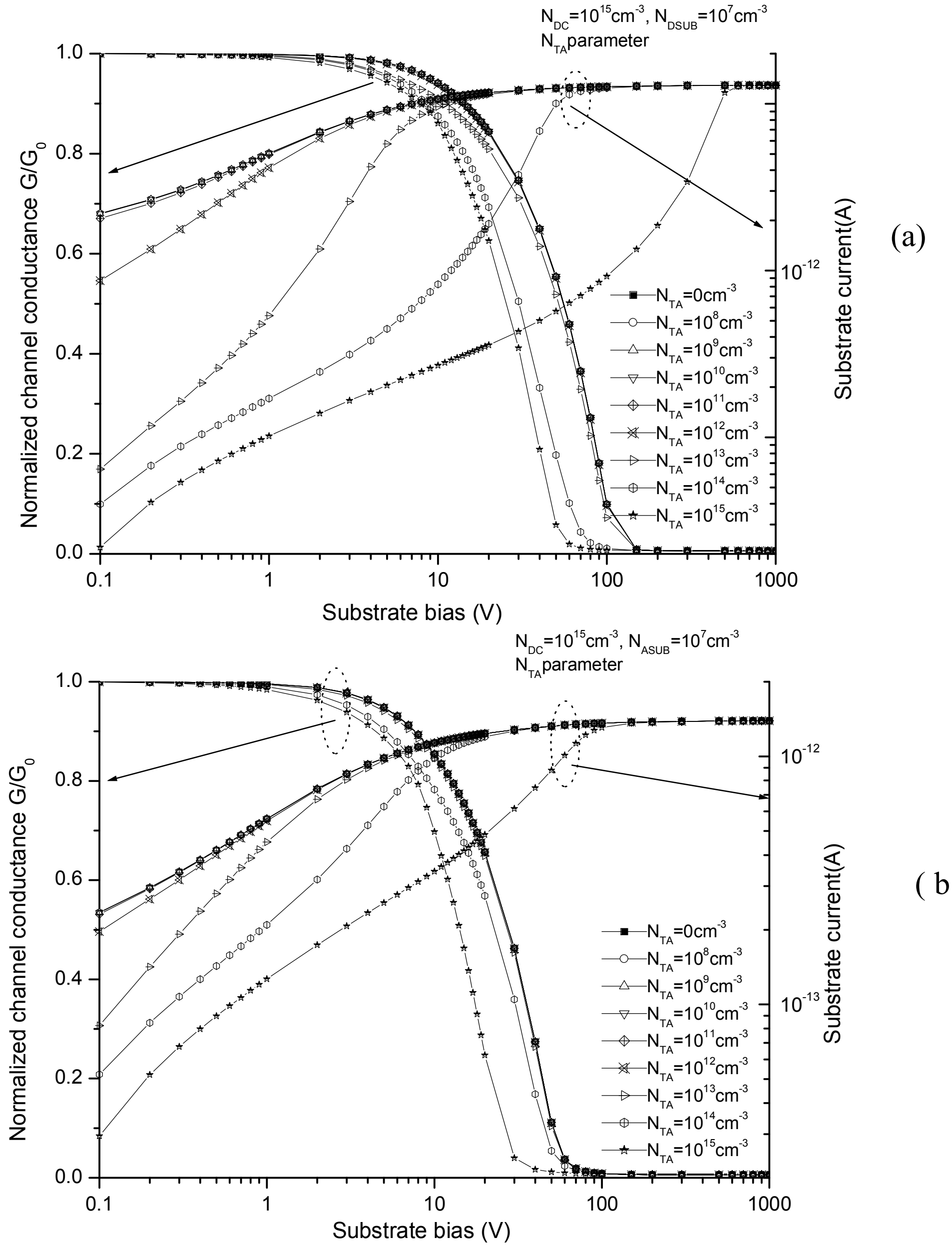


Fig 4.5 : The normalized conductance and the substrate current as function of substrate voltage with the acceptor trap density as a variable parameter: (a) for the nn^- structure and (b) for the np- structure.

The conductance is reduced at a voltage smaller than the one in the case of their absence. This is evident since acceptors gives the substrate a p-type like semiconductor, with a high density than in previous case (without traps). For the densities not much higher to 10^8 *cm* the effect is very small.

For the substrate current; it decreases with increasing deep acceptor density; the current is always a generation type. It is proportional to the width of space charge region (W_S) which is mainly located in the substrate side of channel-substrate junction. When the deep acceptors density increases; the width decrease since $W_s \propto \frac{1}{\sqrt{N_{TA}}}$ and hence the current decreases according to $I_{gr} \propto W_s \propto \sqrt{\frac{V}{N_T}}$.

Another phenomenon is observed; that is the current for low deep acceptors densities has the same shape as in the case of their absence. For high densities the shape change dramatically; especially for the nn$^-$ structure. This is more clarified by plotting the electron, hole and ionized trap densities (fig 4.6). The ionized trap density increase the hole density in the substrate while reducing those of electrons.

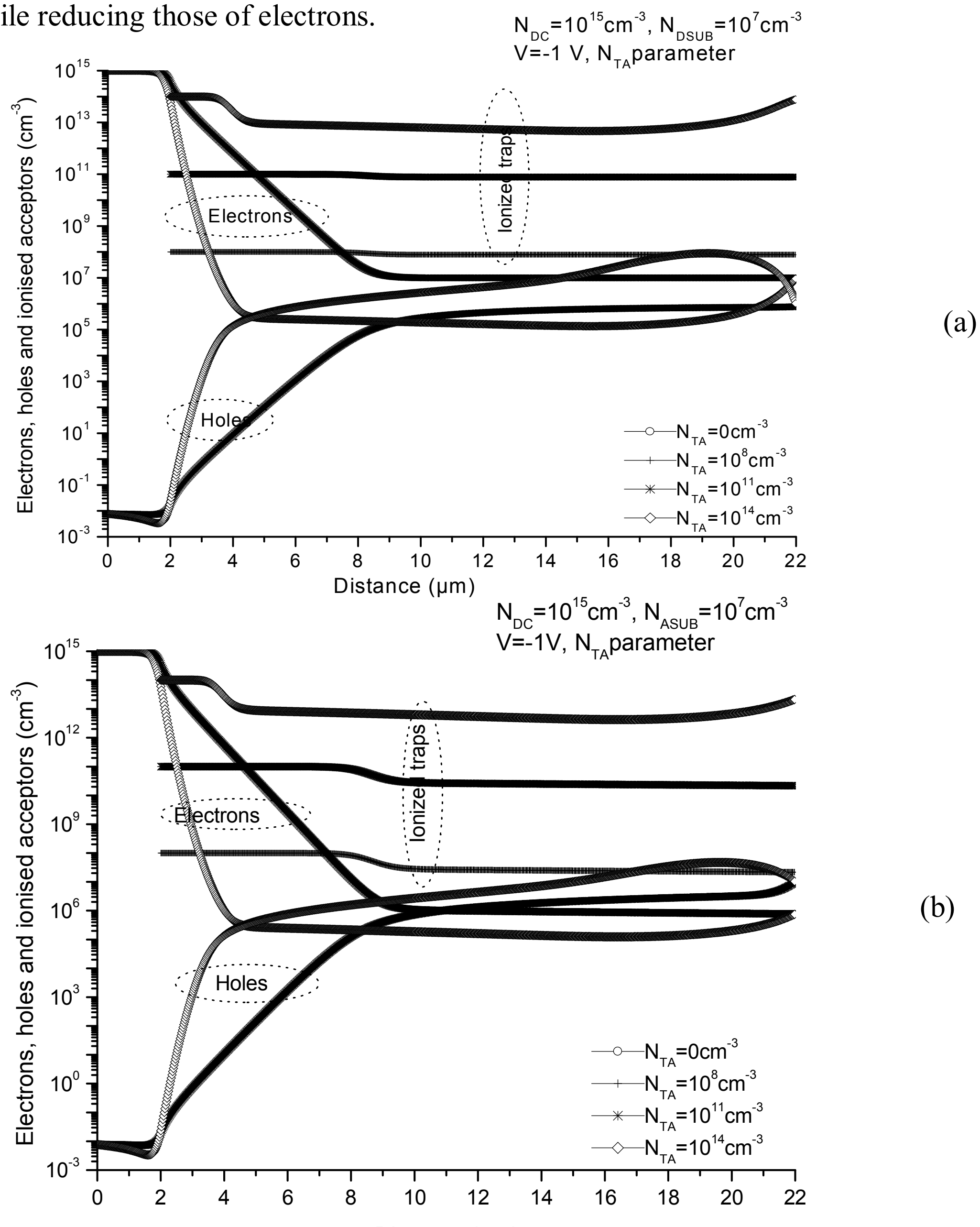


Fig 4.6: The electrons and holes and ionized acceptors distribution in the (a) nn$^-$ and (b) np$^-$ structures.

4.3.1 Temperature effect

The effect of temperature on the backgating and substrate current is presented in fig 4.7.

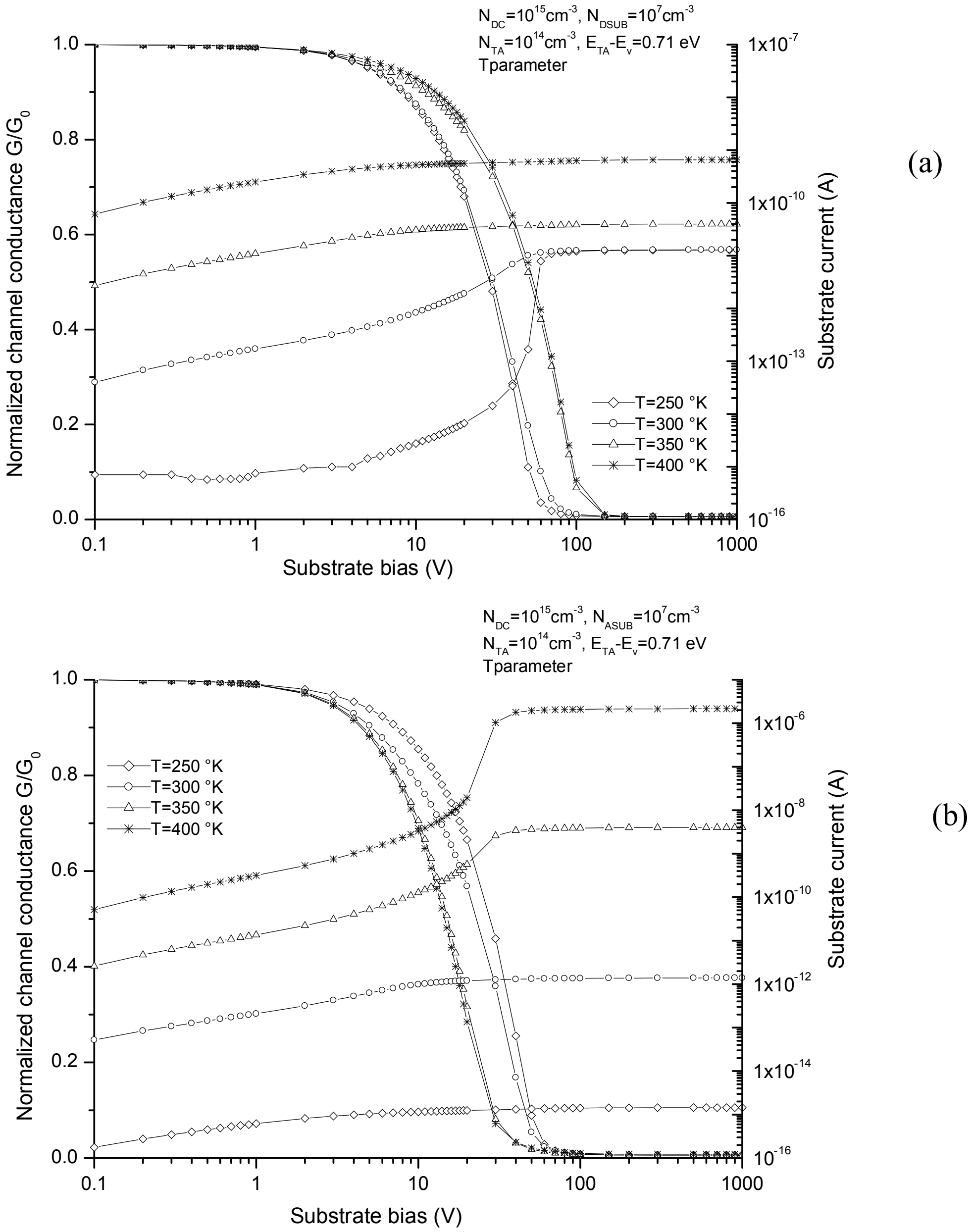


Fig 4.7: The temperature effect on the backgating and substrate current in the presence of the acceptors only in nn$^-$ structure (a) and np$^-$ structure (b).

In the nn$^-$ structure, as the temperature increases the ionized deep acceptor increases and reduce the n-type property of the substrate, hence the numbers of electrons passing from the channel to the substrate decreases resulting in the increase of the conductance. In the np$^-$ structure, as the temperature increases, the ionized acceptors increase the p-type property of the substrate and hence decreases the conductance of the channel.

It is also observed that deep acceptors cause the generation and TFL currents. Acceptors give the substrate the p-type. If they are not fully ionized, the substrate current is of a generation type. But when they become totally ionized, the current is of TFL type. This is shown in figure 4.8 and 4.9.

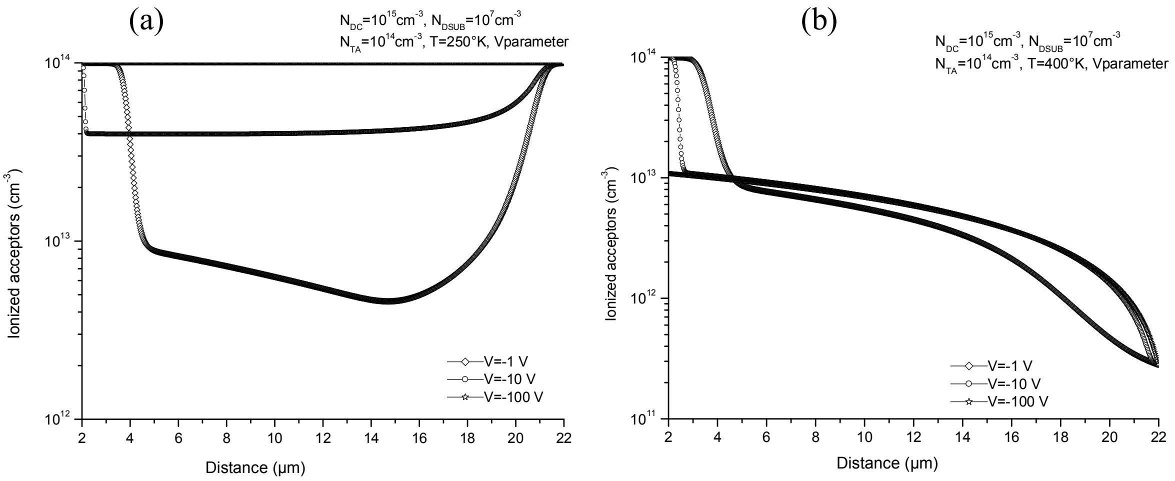


Fig 4.8: Ionized acceptors in (a) nn$^-$ structure at 250°K and (b) 400°K.

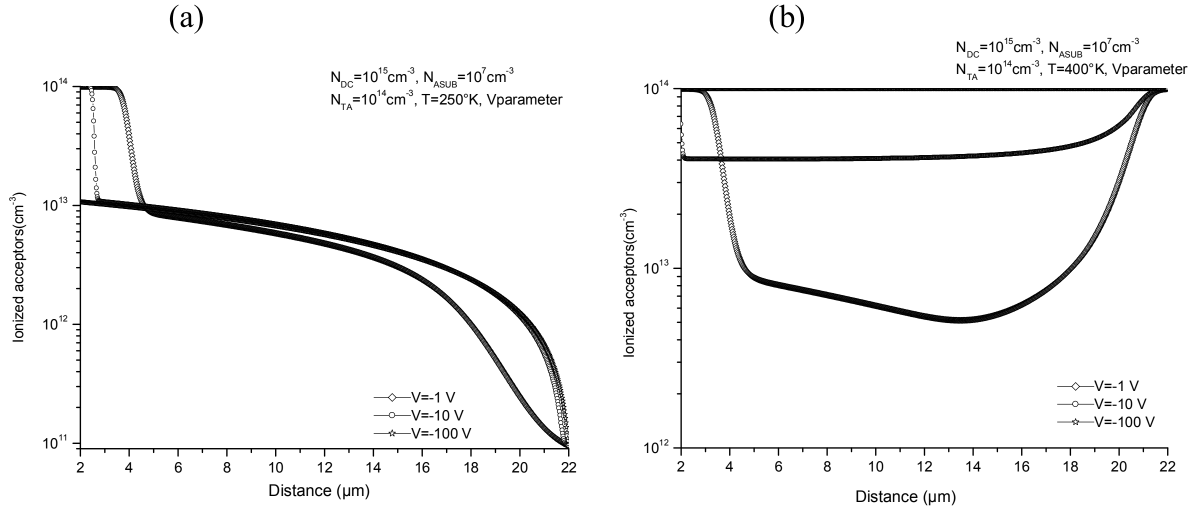


Fig 4.9: Ionized acceptors in (a) np$^-$ structure at 250°K and (b) 400°K.

In the case of the nn$^-$ structure and for 250 °K, the acceptors are fully ionized when the voltage is at about 100 V. For 400 °K, they are not fully ionized at all voltages. In the case of the np$^-$ structure for 250 °K, the ionization of acceptors is not fully nowhere, while for 400 °K TFL occurs for 100 V.

The temperature effects the currents because of the temperature dependence of $n_i \propto (T/300)^{3/2} \exp\left(\frac{-E_g}{2K_BT}\right)$. Therefore the current scales with the ratio $n_i(T_1) / n_i(T_2)$.

4.4 The effect of donor traps

If deep donor taps located at E_T= 0.68 *eV* from E_v (a typical value for the well know EL2) are added in the substrate; the normalized conductance and the current are presented in fig 4.10, for the structures nn$^-$ (a) and np$^-$ (b).

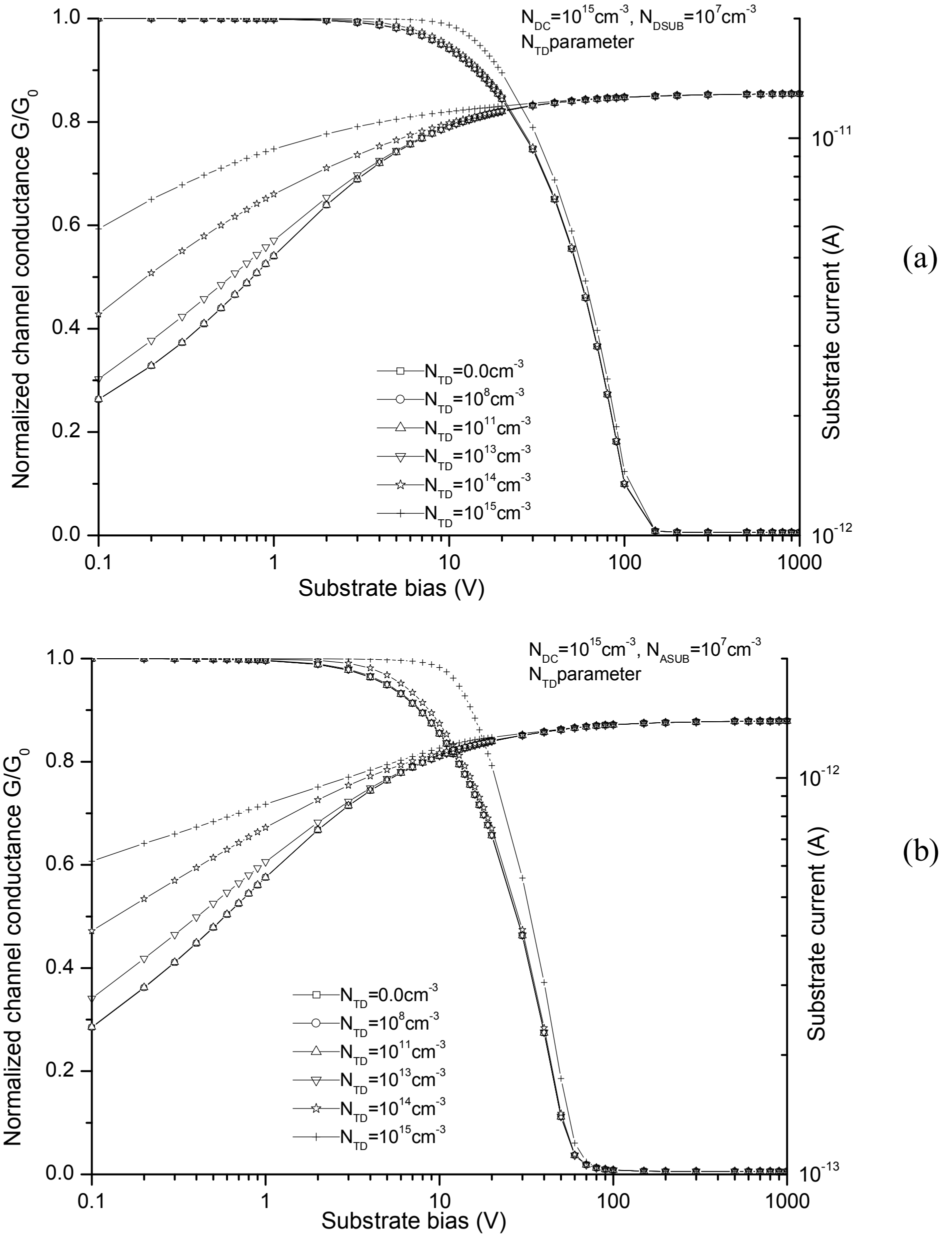


Fig 4.10: The donor traps effect on the channel conductance and substrate current for the nn$^-$ (a) and np$^-$ (b) structures in the absence of acceptor traps.

The deep donors reduce the backgating slightly in both structures. In the np^- structure, it makes the substrate less p-type and hence reduce the effective p-type density in the substrate so that the depletion region at the channel side is reduced. As the deep donor density increases the width of the space charge in the substrate is increased but it decreases in the channel. Where

$$\begin{cases} N_D W_c = N_{Aeff} W_s \\ W_s \propto \sqrt{\dfrac{1}{N_{Aeff}}} \text{ and } W_c \propto \sqrt{N_{Aeff}} \end{cases}$$

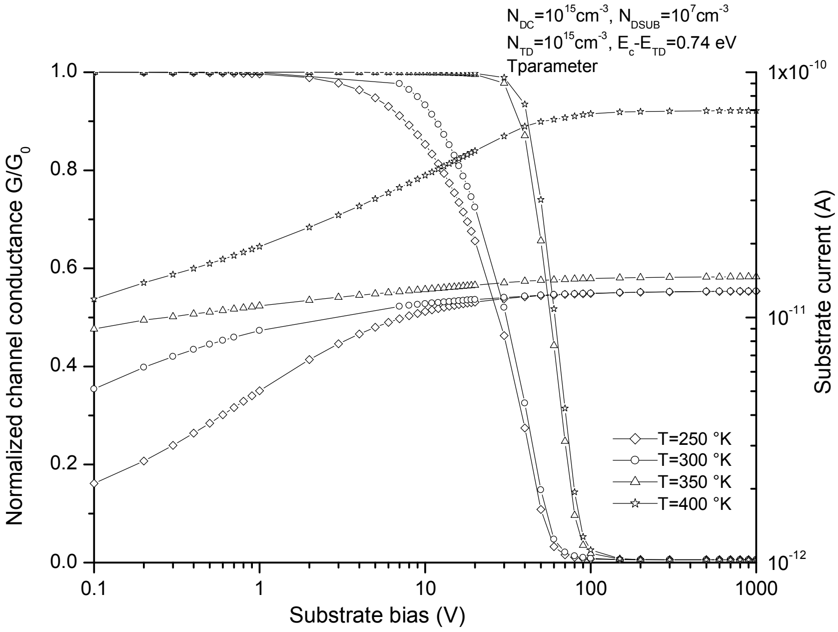
where N_{Aeff} is the effective acceptor density into the substrate.

In the nn^- structure, deep donors make the substrate more n-type. This reduces the number of electrons injected from the channel to the substrate and hence increases the channel conductance.

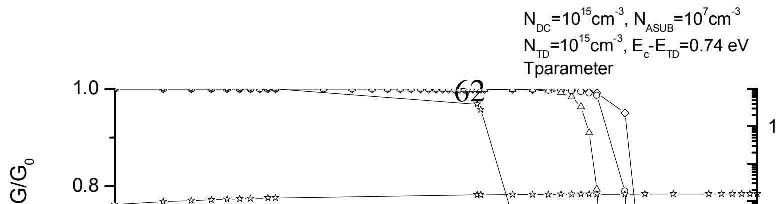
In many cases this particularity (presence of donors only) is of no great interest since it is well known that deep acceptors are mainly responsible for backgating while deep donors reduce it and in the case of GaAs both type of traps are always present see for example [1]. This case is the most important and will be developed in details in the next sections.

4.4.1 Temperature effect

Fig 4.11 represents the temperature effect on the channel conductance and substrate current in both structures, in the case where the substrate contains only deep donors.



(a)



In the case of np$^-$ structure as temperature increases, the ionized donors density increases giving the substrate less p-type. this tends to eliminate the generation and TFL currents since they reduce the depletion region. In the nn$^-$ structure, the more ionized deep donors widen the accumulation zone. For the conductance, with increasing temperature the ionized donors give the nn$^-$ structure more n-type which means that for decreasing the conductance it must give more tension which is shown in fig 4.13.1. Will in the np$^-$ structure it become less p-type hence less tension to reduce the conductance proved by fig 4.13.2. For the increasing of substrate current. The increase may be due to the diffusion current. Fig 4.12. shows the change of the band bending with increasing temperature which lead to more ionization of donors.

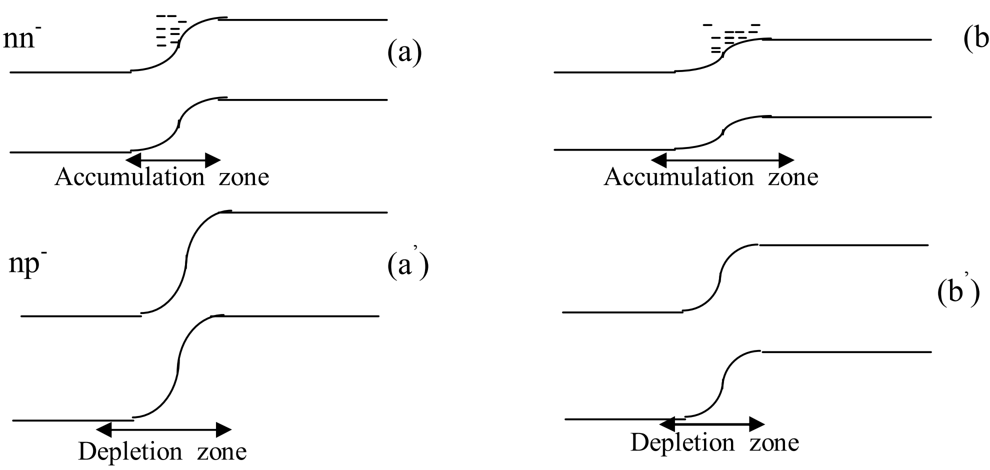
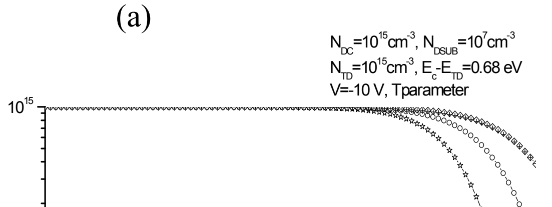


Fig 4.12: The band bending (a, a') at 250 °K and (b, b') at 400°K for the two structure when the substrate contains donors.

(a)



(b)

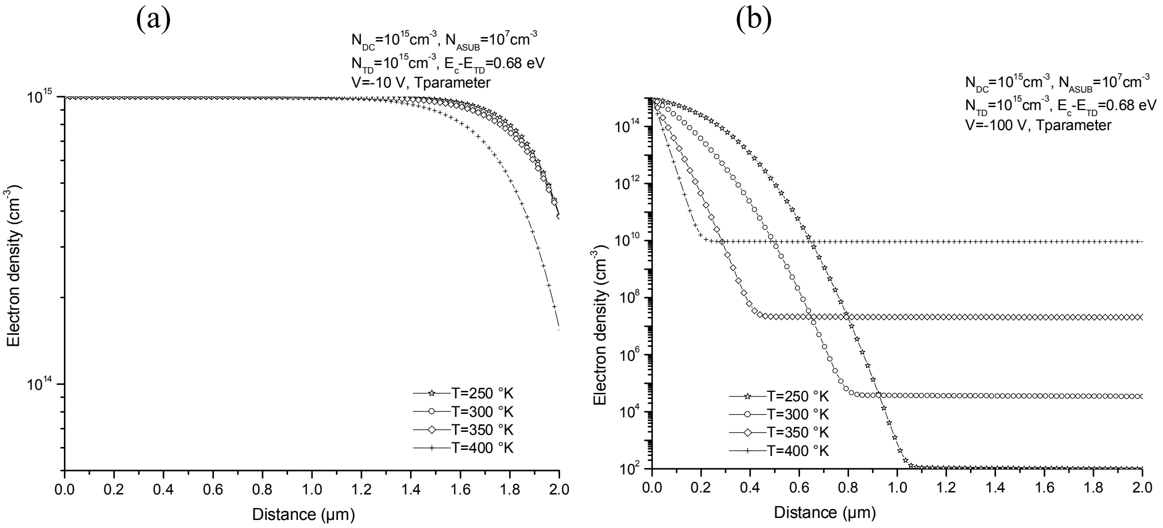


Fig 4.13.2: Electrons distribution with respect to temperature on an applied negative voltage (a) –10 V and (b) –100 V to the np$^-$ structure.

4.5 The effect of donor traps in the presence of high density of acceptor traps

When deep donors are added in the substrate which contains a high density of deep acceptors the results are presented in fig 4.14.

The increase of the deep donor density increases the current in both structures but increases the threshold voltage in the np$^-$ structure when it reduces it in the nn$^-$ structure. In the case of np$^-$ structure, the compensation of acceptor traps gives the substrate less p-type. Hence the reduction of depletion region yield the increasing of channel conductance. In the nn$^-$ structure increasing donor density doesn't only compensate the acceptors but also give the substrate more n-type which lead to more electrons crossing from the channel to the substrate, hence the conductance decreases.

The substrate current increases because of two reasons. The first is the decreases in the hole density in the substrate, the second is the increase in the width of the depletion region within the substrate since the current is partially a generation-type (between generation and ohmic). This behavior will be explained by the relaxation regime in section 4.11. The threshold voltage increases since the p-type substrate requires higher voltage to deplete the channel.

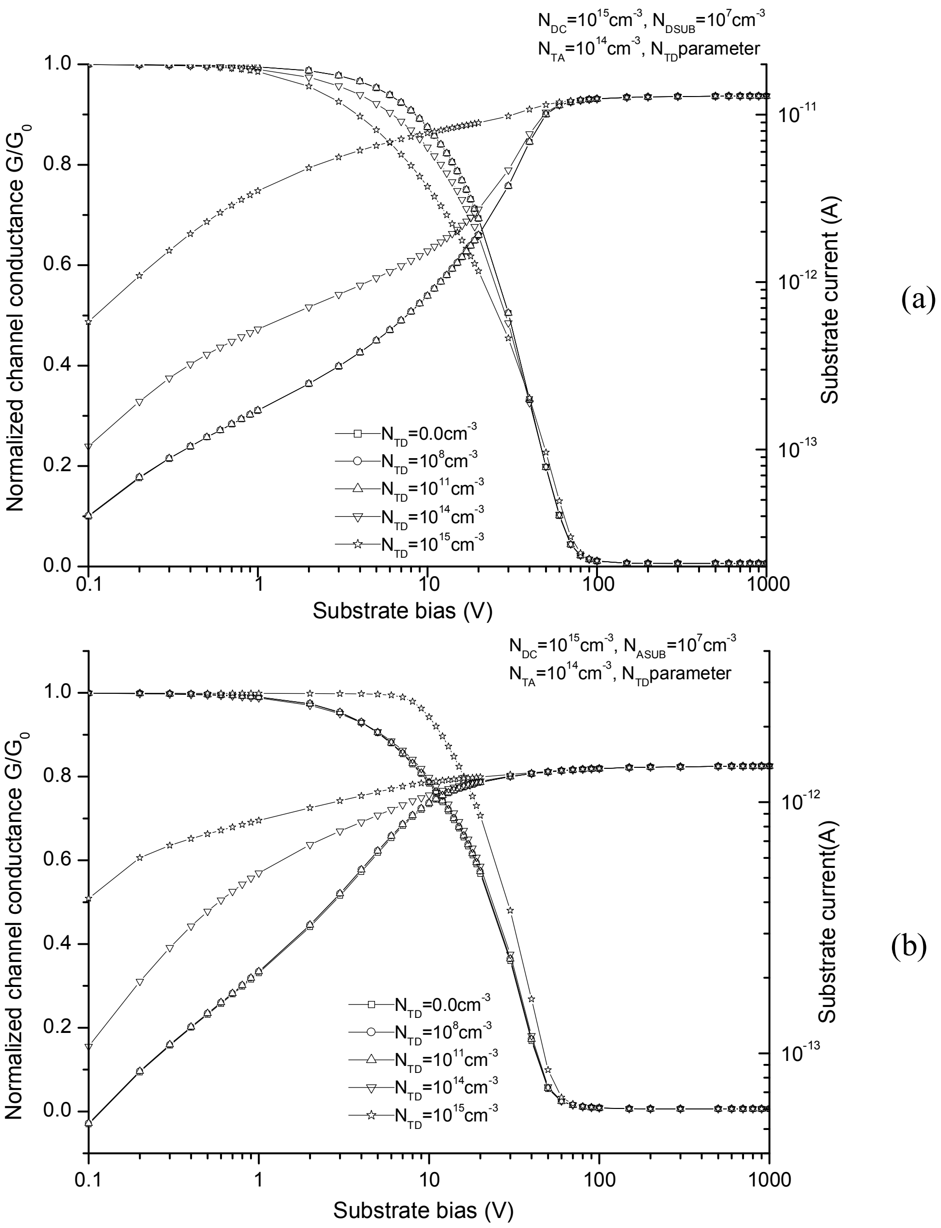
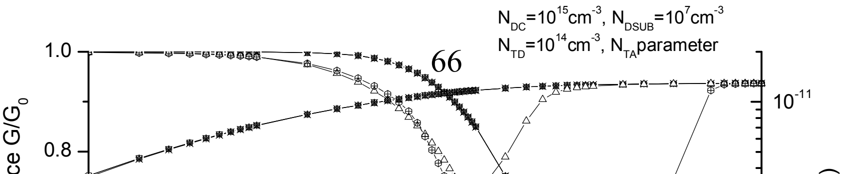


Fig 4.14: The normalized conductance and substrate current in the presence of deep acceptors with deep donors as parameters in nn^- (a) and np^- (b) structures.

Another phenomenon is observed and it is different into the two structure. In the nn^-, a TFL type current is observed while it is absent in the np^- structure. This can be explained by plotting the charge of the deep acceptors in the substrate (fig 4.15). It is observed that the TFL type current appears when ionized deep acceptors are less compensated by deep donors. In other words deep acceptors enhance the appearance of TFL while deep donors reduces it by compensating deep acceptors and making the substrate less p-type.

4.6 The effect of acceptor traps in the presence of high density of donor traps

Fig 4.16 represents the effect of acceptor traps in the presence of high density of donors. The acceptors increase the backgating (decrease the threshold) and decrease the substrate current especially when their density exceed that of the donors.



4.7 The effect of energy level position

4.7.1 Donor traps

If the energy level position of donors traps varies across the forbidden band, the responses of the nn$^-$ and np$^-$ structures are illustrated in fig 4.17.

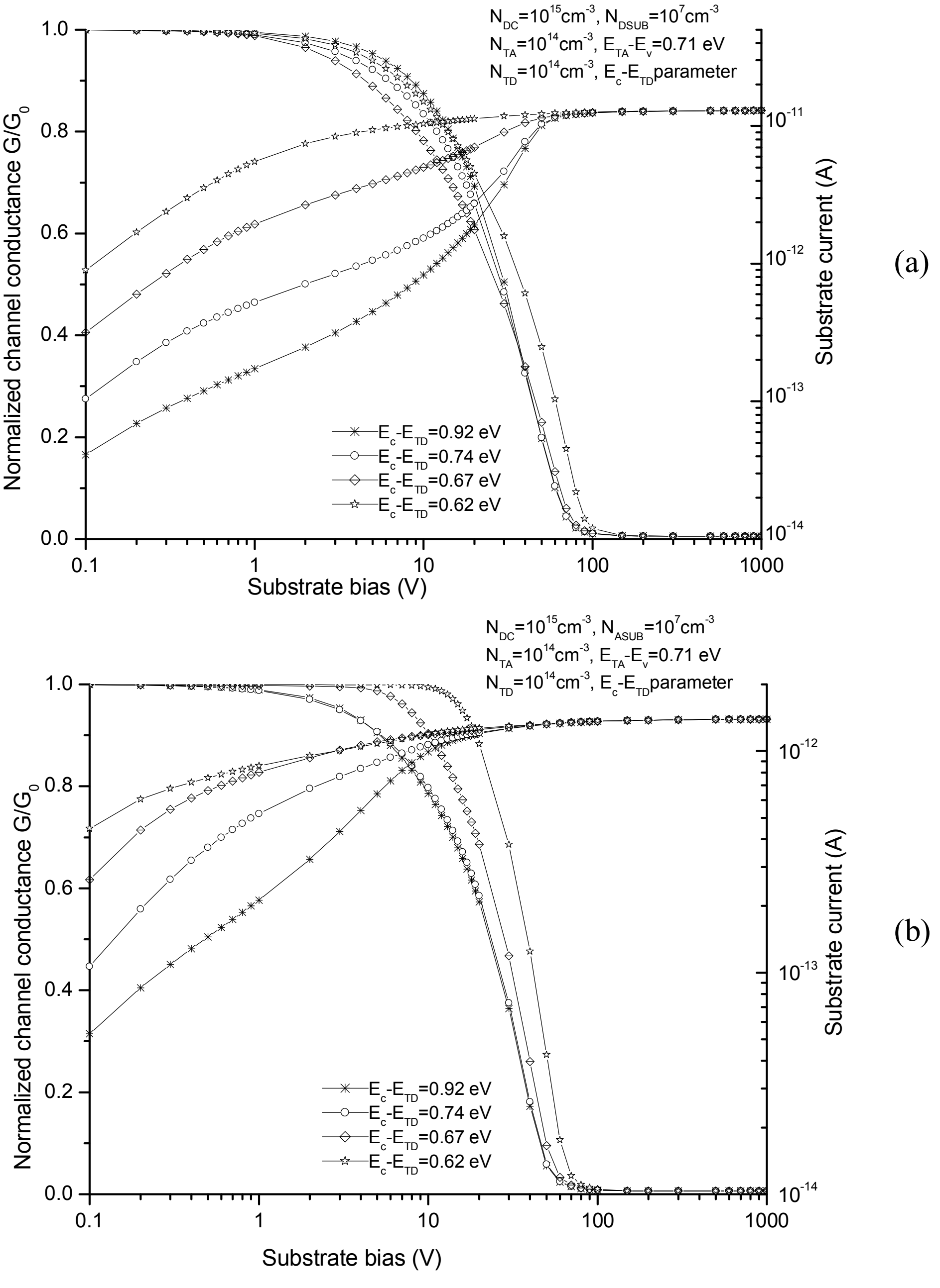


Fig 4.17: Channel conductance and substrate current versus substrate voltage in (a) nn$^-$ and (b) np$^-$ structures, when N_{TA}=10^{14} cm^{-3} (0.71eV) and N_{TD}=10^{14} cm^{-3}, and the parameter is the energy position of donors traps.

In these cases when the donor level is closer to the conduction band; their efficiency (ionization) increases; therefore; the threshold for backgating increases. Hence; this is very important results since it can be suggested that in order to reduce backgating, one can add large density of deep donors with less deep energy (closer to conduction band).

The substrate current increase and change from TFL to generation as explained in previous section.

4.7.2 Acceptors traps

Since the acceptors traps are those the responsible of backgating, their position in forbidden gap is also important. Fig 4.18 illustrates their effect when their energy position varies. For the conductance, it decreases when the acceptors traps are more close to the valence band where their ionization is more important. They extend the space charge region at the channel-substrate interface in channel side. For the substrate current, it is known that if the traps are more ionized, the depletion layers shrink and then the current decrease since it is a generation type proportional to the space charge region width.

It is also observed that the curve ionized deep acceptor are, the more probable that TFL current appears.

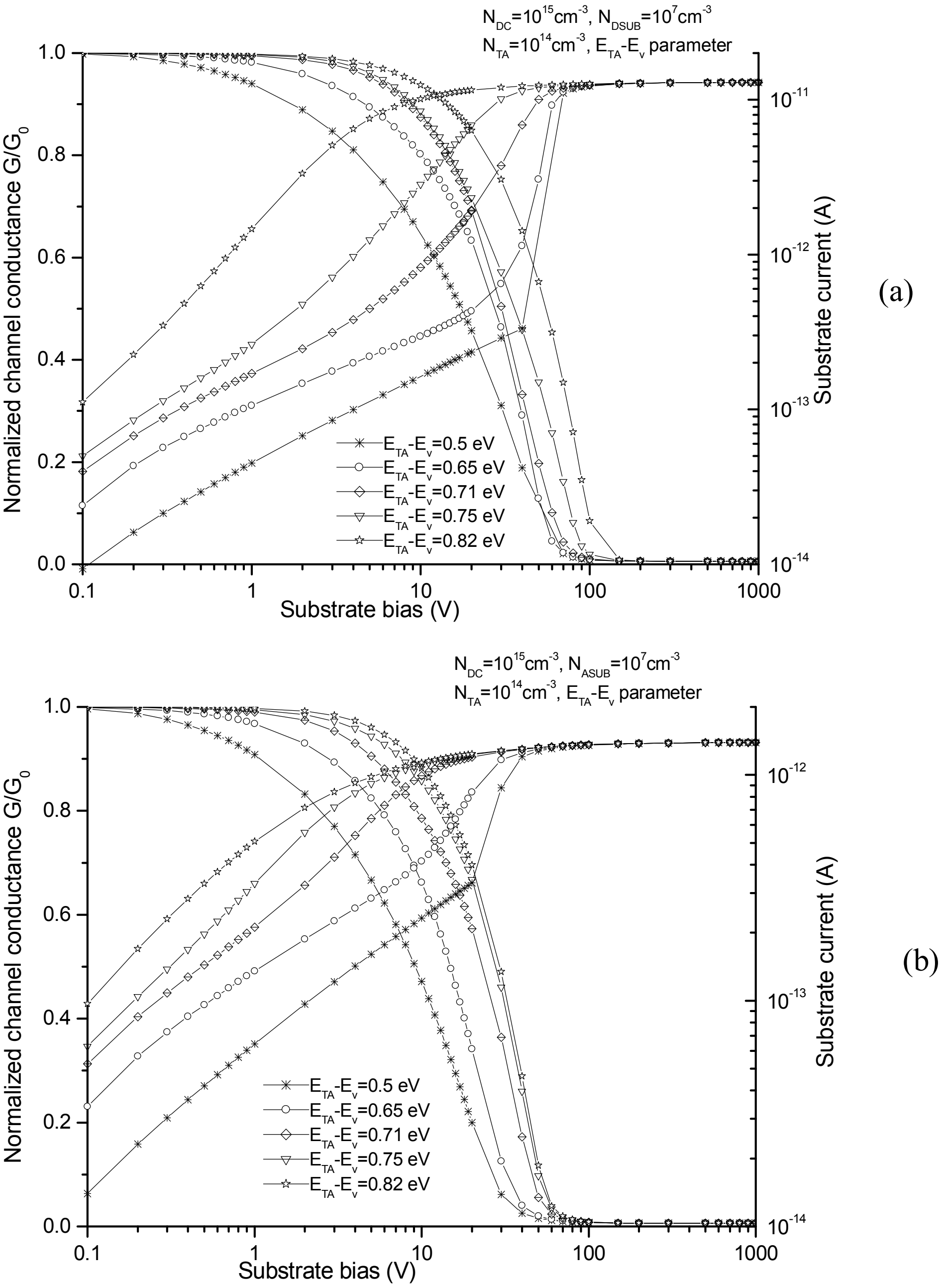


Fig 4.18: Channel conductance and substrate current versus substrate voltage in nn$^-$ (a) and np$^-$ (b) structures, when $N_{TD}=10^{14}$ cm^{-3} (E_c-0.74 eV), $N_{TA}=10^{14}$ cm^{-3} and the energy position of acceptor traps as a parameter.

4.8 BACKGATING WITH AND WITHOUT THRESHOLD

4.8.1.1 The donors effect

At high deep donor density the conductance remains constant, but beyond a certain value of applied voltage it drops rapidly; in both cases. This is the case of backgating with threshold voltage. As previously mentioned that the donors reduce backgating. Fig 4.19 demonstrates this. When the donors are large than acceptors their effect becomes more apparent. Hence to eliminate the acceptors influence we compensate it with donors which increase the electron density and lower that of holes. This is shown in fig 4.20.

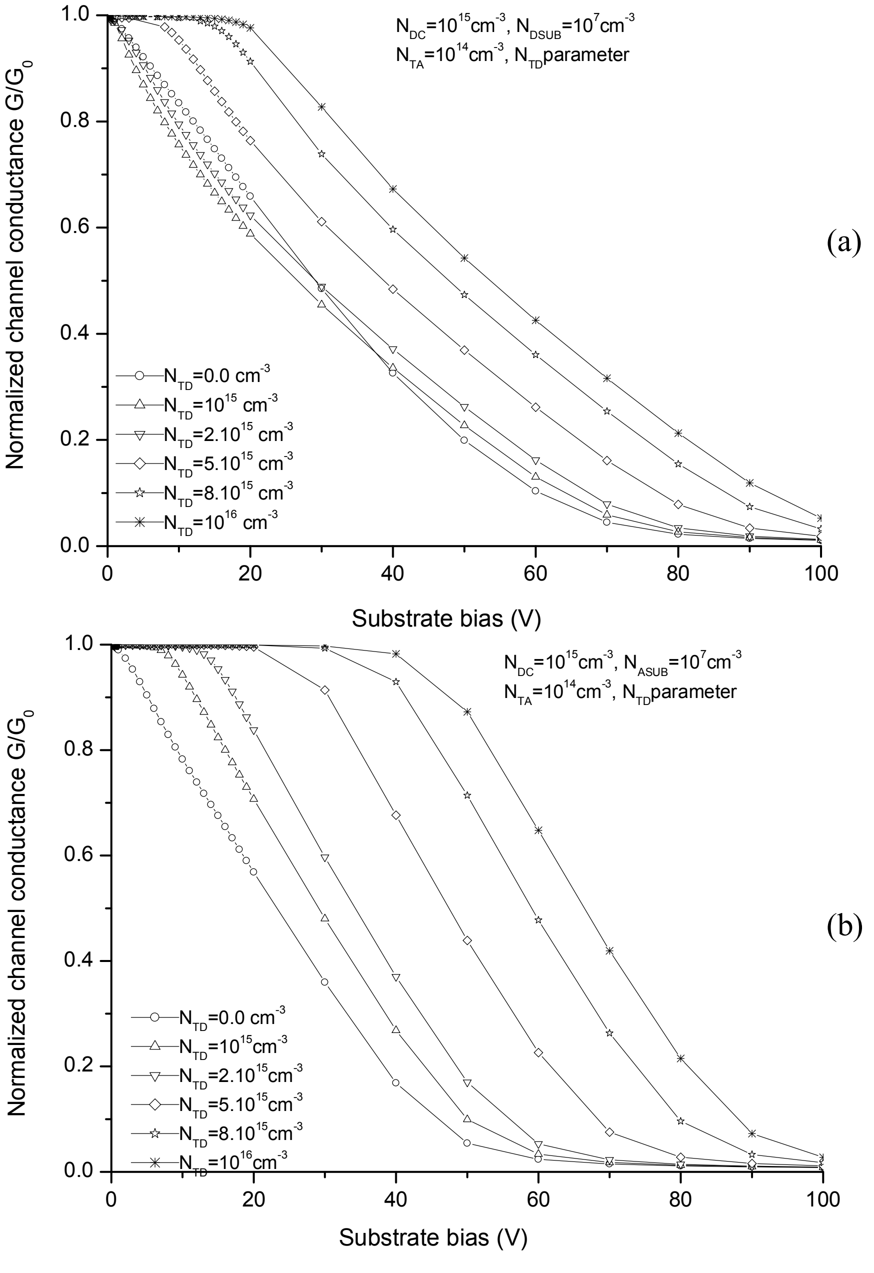


Fig 4.19: Illustration of the normalized channel conductance drops versus the substrate voltage in nn^- (a) and np^- (b) structures.

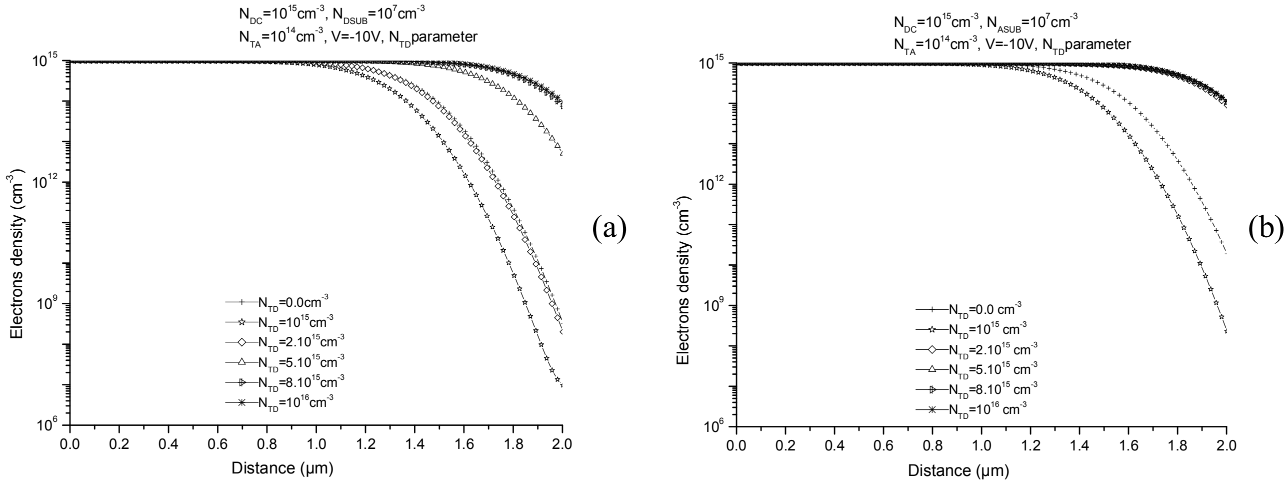


Fig 4.20: The effect of high density of deep donor in the presence of acceptor traps on the electron density distribution in the channel for the nn$^-$ (a) and np$^-$ (b) structures.

We observe at 10 V the backgating appears only when the deep donors are at 10^{15} cm^{-3} while for larges densities there is no backgating at this voltage.

4.8.1.2 The effect of the energy level of the donor trap

In these cases, we take the position level of donors traps as parameter in order to more improve that the backgating is further reduced for levels closes to the conduction band. Fig 4.21 shows this effect.

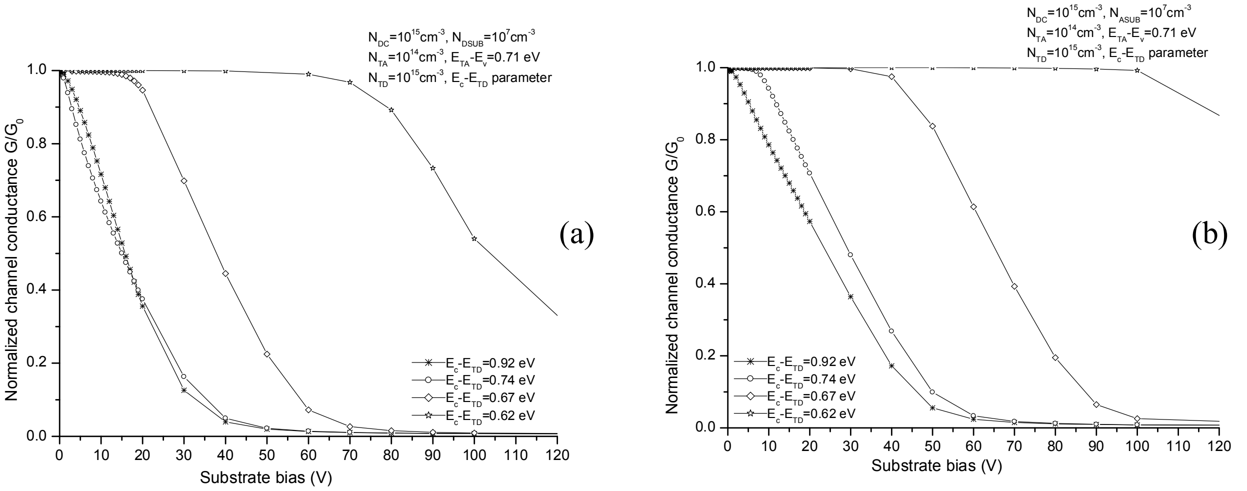


Fig 4.21: The Channel conductance versus the substrate bias. The deep acceptor density is 10^{14} cm^{-3} at E_{TA}-E_V=0.71 eV. The deep donor density is 10^{15} cm^{-3} with its energy position as a parameter, in nn$^-$ (a) and np$^-$ (b) structures.

4.8.2.1 the acceptors effect

As previously mentioned the acceptors increases the backgating and the increase of their density makes their effect more appears.

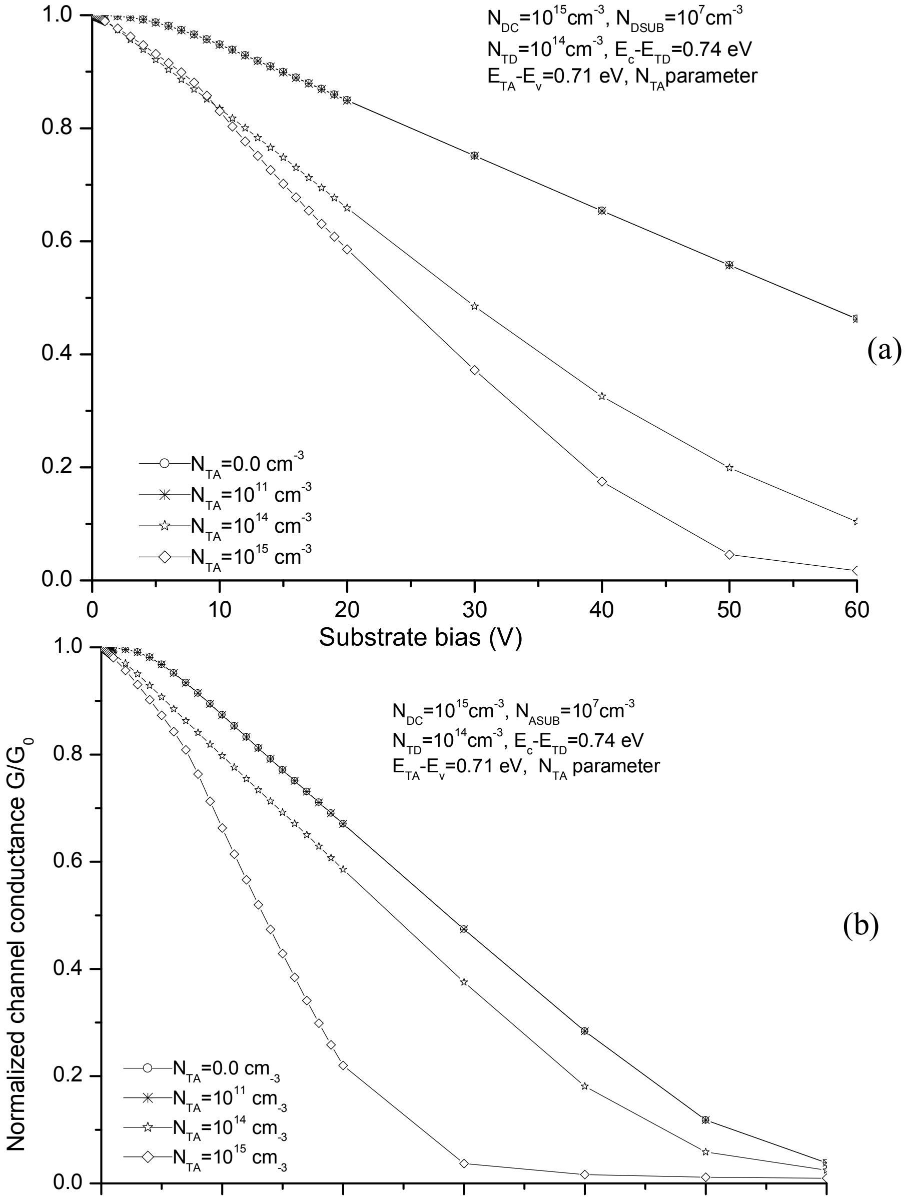


Fig 4.22: The effect of increasing acceptor density on the normalized channel conductance drops versus the substrate voltage in nn^- (a) and np^- (b) structures.

4.8.2.2 The effect of energy level of the acceptor trap

When the acceptor levels are far from the valence band the holes contribution become less important which implies that the substrate is less p-type, hence the space charge region inside the channel is smaller which means that the conduction cross section of the channel is less affected; resulting in a constant channel conductance.

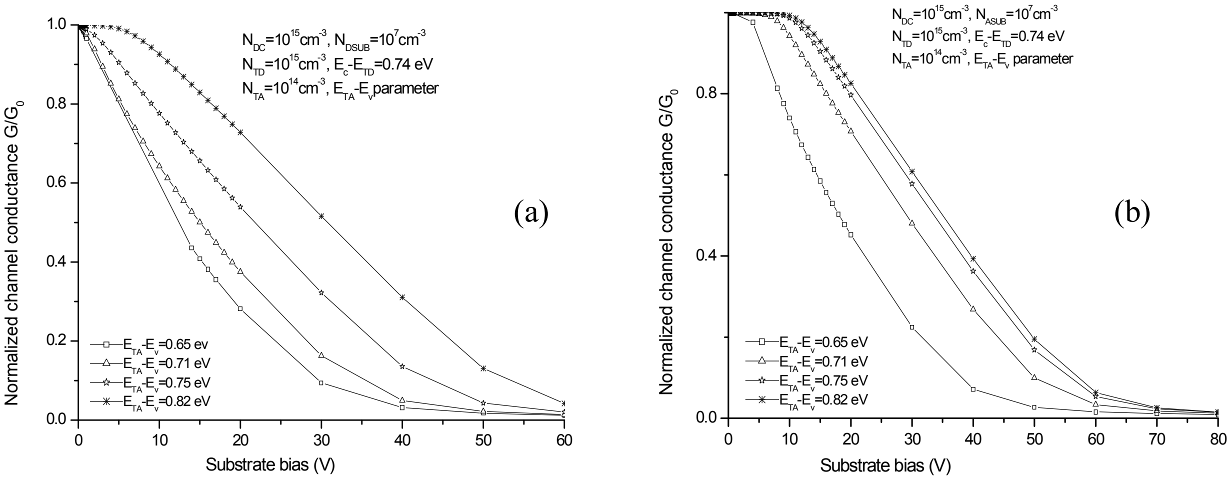
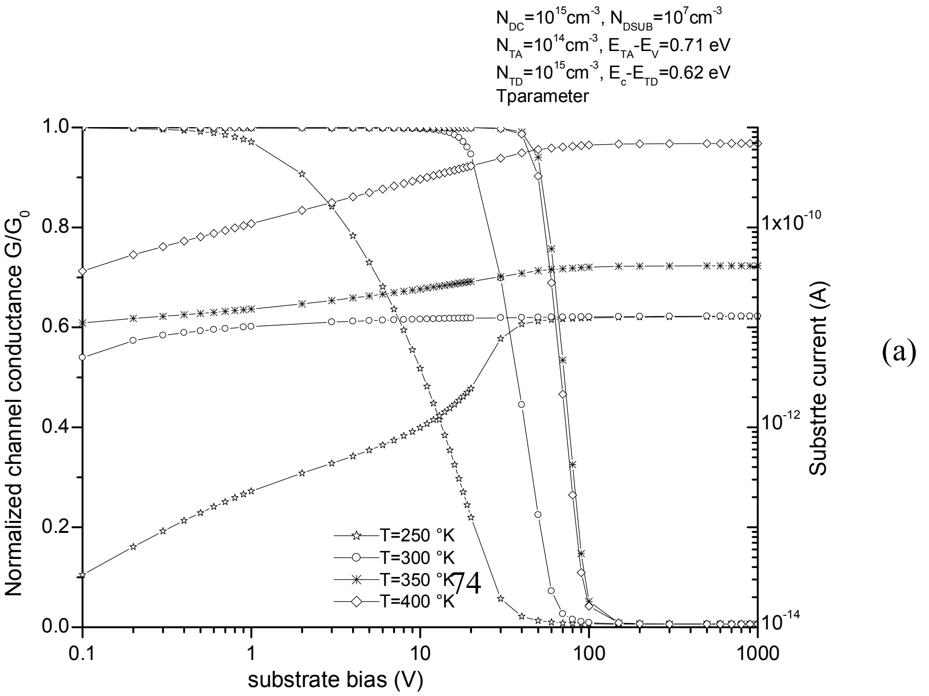


Fig 4.23: The Channel conductance versus the substrate bias. The deep donor density is 10^{15} cm^{-3} at $E_c-E_{TD}=0.74$ eV. The deep acceptor density is 10^{14} cm^{-3} with its energy position as a parameter in nn^- (a) and np^- (b) structures.

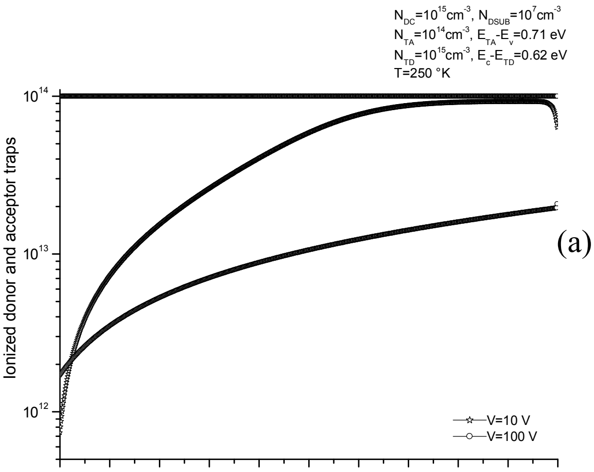
4.8.3 Temperature effect on the threshold voltage

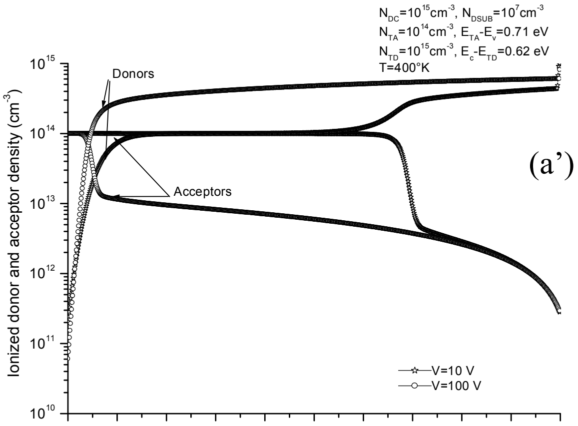
In the case when the deep levels are both present in substrate. The acceptors density is about 10^{14} cm^{-3} located at 0.71 eV from the Valence Band and the donors density is about 10^{15} cm^{-3} and located at 0.62 eV from the conduction band. The effect of the temperature on the backgating and substrate current is presented in figure 4.24.

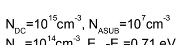


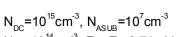
For the nn$^-$ structure, the Fermi level is closer to the conduction band, all acceptors are more ionized at 250 °K hence the TFL current appears. As the temperature increases, the ionization of acceptors does not change while that of deep donors change mainly at 400 °K.

for the np- structure, the fermi level is closer the valence band, the donors are more ionized at 250 °K. Increasing temperature increases the ionization of acceptors yielding the appears of TFL current at 400 °K. the increase of acceptors compensate the donors and reduce their concentration. This is proved by fig 4.25.









4.8.4 Channel-substrate spacing effect on the threshold voltage

The effect of the substrate length which is the channel substrate spacing on the backgating and substrate current is illustrated in fig 4.26. For the nn$^-$ and np- structures when the substrate contains a high density of donors and acceptors.

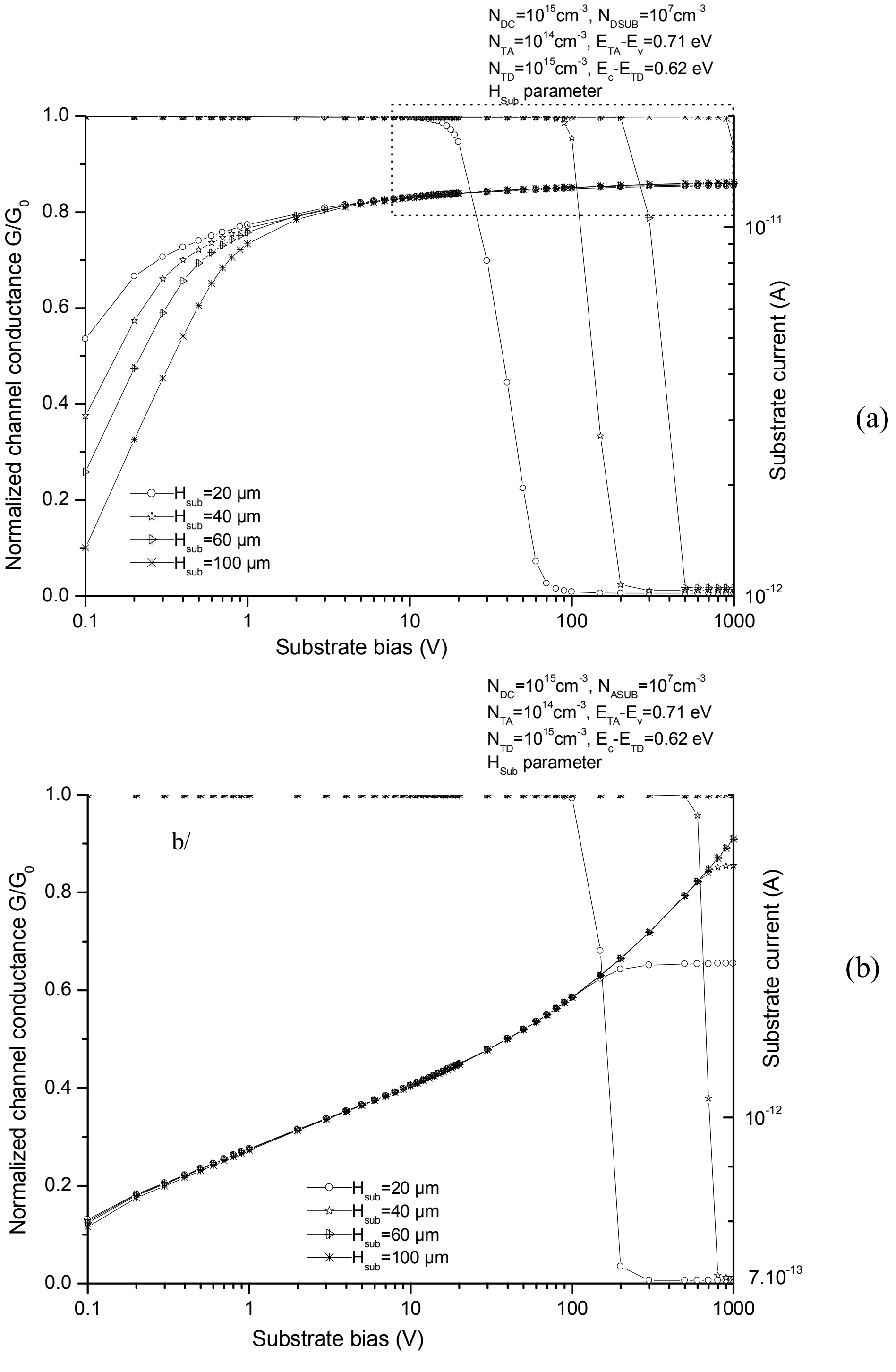


Fig 4.26: The channel-substrate spacing effect on the threshold voltage, backgating and substrate current.

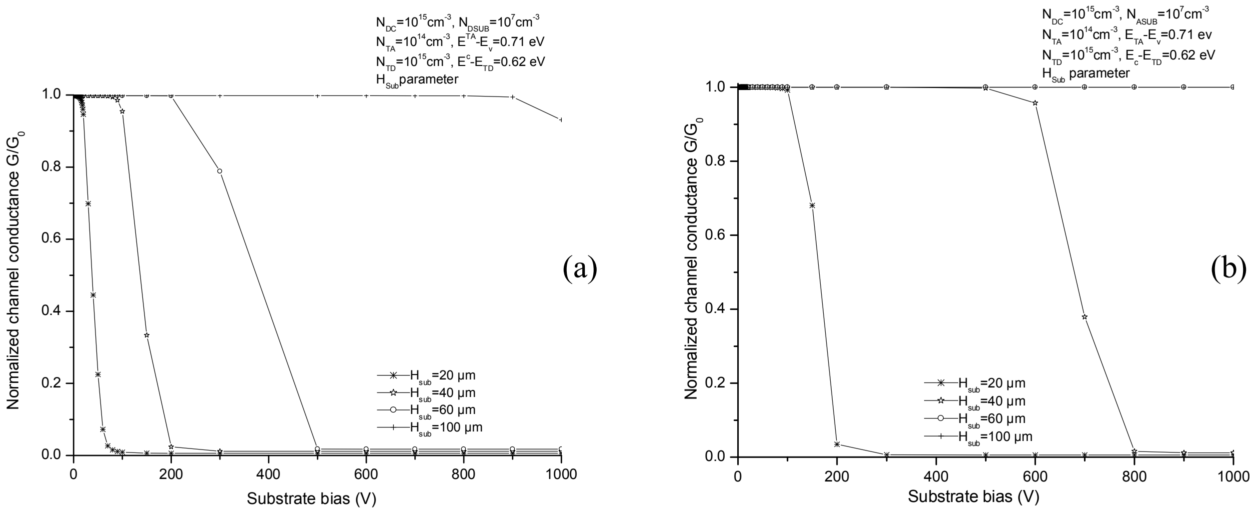


Fig 4.26: The change of threshold voltage according to the channel substrate spacing .

In this last case the backgating is reduced with increasing the substrate length in both structures which is obvious, so the substrate become more able to preclude the reverse tension, hence the threshold increases. For the saturation of substrate current, is also due to the saturation of velocity, therefore the saturation in substrate of 20 µm occurs before those of bigger lengths. hence, for achieved the saturation in longer structures we need more voltages. this is proved by the relation $I=A\cdot\sigma\cdot E$ where $E=\frac{V}{L}$. We can also observe that there is a good coincide with the decreasing of the conductance and the saturation of substrate current.

4.9 GaAs as relaxation material

4.9.1 Introduction

As summary of the substrate current–voltage characteristics, the deep donors have the effect of eliminating the generation current, since it makes the substrate less p-type, hence the absence of depletion region. The current in this case tend to be constant with increasing donor density. On the other hand, the generation and TFL currents appears in the presence of deep acceptors in the substrate. Therefore, we will present in discussion about the relaxation phenomenon for the latter case only (presence of acceptors).

4.9.2 Substrate current and the relaxation phenomenon

In both structures the current is almost linear (most probably a diffusion type current) before its slope decreases to give generation current. This is caused by the increasing space charge width. Therefore the resistance increases. The change in this resistance denoted ΔR is proportional to the change ΔW in the space charge layer width, which in turn is proportional to $(\Delta V)^{1/2}$. Since $\Delta R = \Delta V / \Delta I$, it follows that $\Delta I \cong (\Delta V)^{1/2}$, which means a sublinear dependence with slope $s = 1/2$ (R_2). This is a well known phenomenon called the relaxation regime [5, 6]. At a certain voltage; the current increase suddenly. This is related to the well know space charge limited current (SCLC) or TFL [24, 44] where the current is proportional to V^{α} ($1 \langle \alpha \langle 2$). In R_4 region; the structure behave as a simple ohmic resistance. The current is proportional to voltage (ohmic) in the case where the mobility is constant, and saturated when the mobility is field dependent.

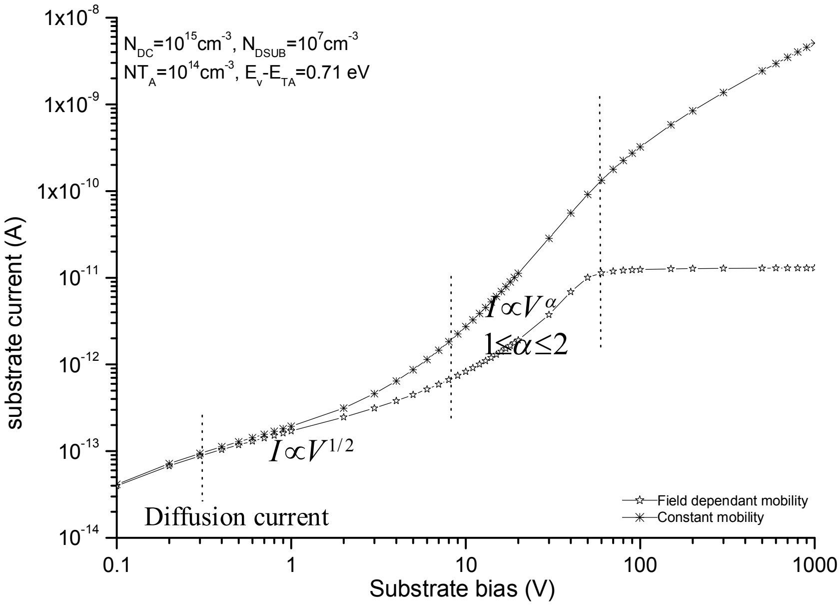


Fig 4. 28: The substrate current variation as function of reverse bias for the nn- structure.

4.12 The effect of substrate doping

The substrate doping is an important factor. Since one can observe that in the structure where the substrate is more doping the current voltage characteristics and the backgating is more clear. For example, we have chosen two other structures, where the channel has doping density of $N_D=10^{15}$ cm^{-3}, for the first the substrate is initially n-type with shallow level density of 10^{11}cm^{-3}. For the second, the substrate is initially p-type where the density of the shallow level is about 10^{11} cm^{-3}. Changing certain parameters give the follows.

4.10.1 The effect of acceptors

In this structure, the acceptors has the same effect as the previous. With increasing their density, the generation and TFL current appears more and the backgating increase.

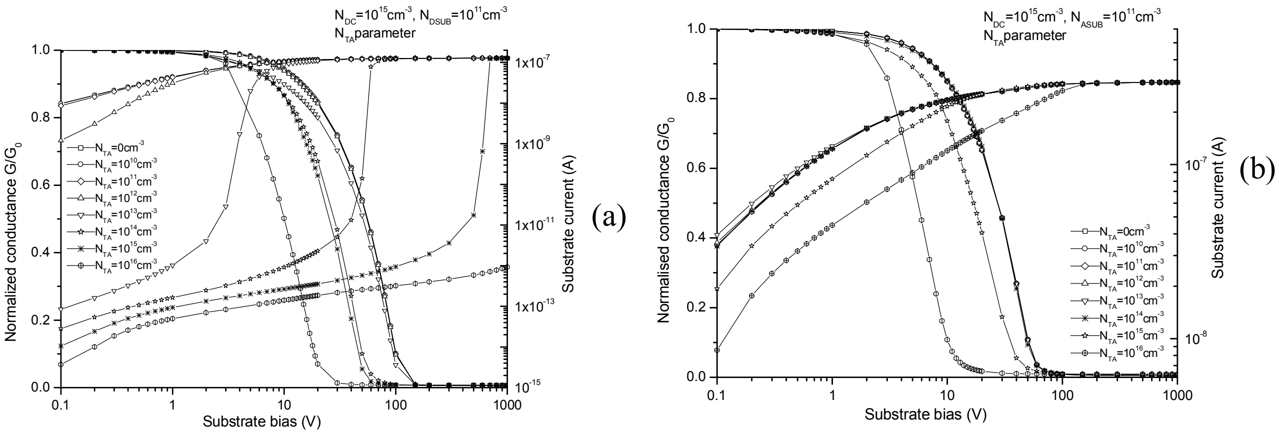


Fig 4.29 : The acceptor effect on backgating and substrate current in n15n11 (a) and n15p11 (b) structures.

4.10.2 The effect of donors

the same observation are given from fig 4.30. The donors reduce or tend to eliminate the generation and TFL current. In other words the donors tend to reduce the acceptors effect.

In n15n11 structure they decrease the conductance since they make the substrate more n-type which lead to more electrons crossing the channel to the substrate. In n15p11, the donors reduce the depletion region inside the substrate resulting in the decrease of substrate current but in this case we can subject that the donors have a large density yielding them to compensate the acceptors and passing through the junction leading to reduce the backgating.

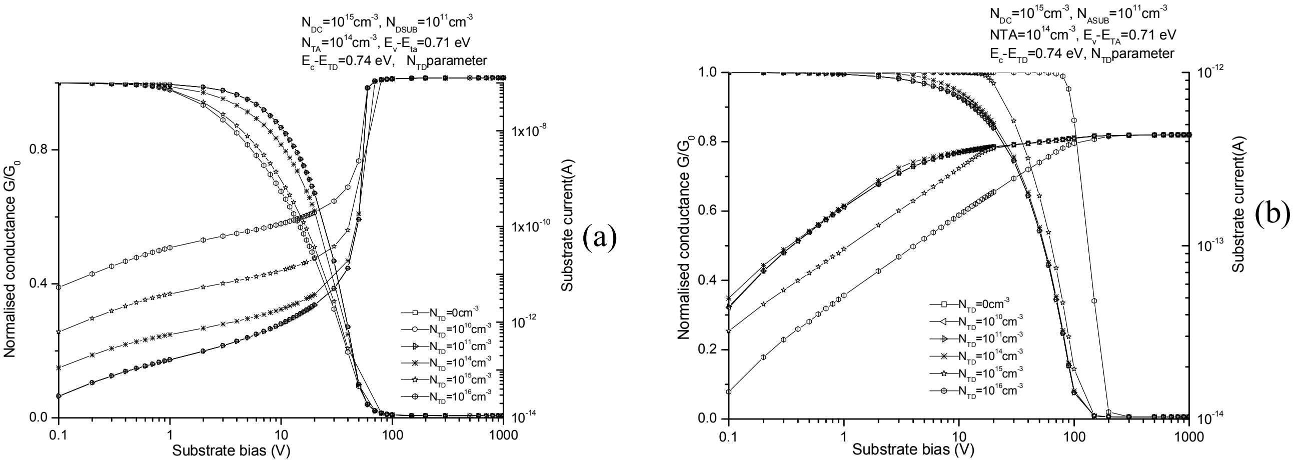


Fig 4.30 : The donors effect on backgating and substrate current in n15n11 (a) and n15p11 (b) structures.

4.10.3 The effect of temperature

In the presence of high density of acceptors and donors, increasing temperature give more ionization to the two type. Fig 4.31 represent the temperature effect on the backgating and substrate current for n15n11(a) and n15p11 (b) structures.

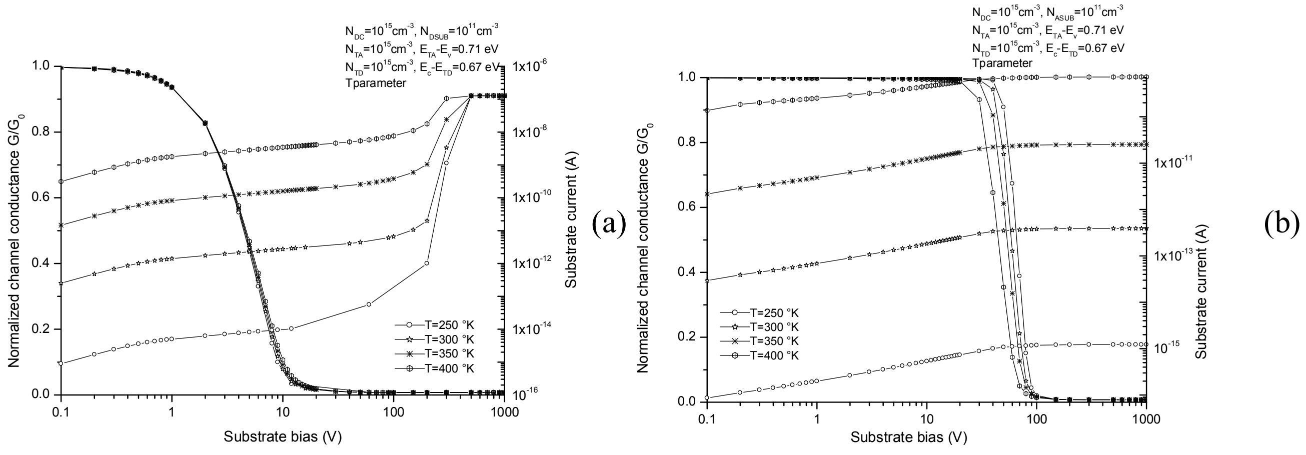


Fig 4.31 : Temperature effect on backgating and substrate current when the substrate contains a large density of donors and acceptors. In n15n11 (a) and n15p11 (b) structures.

4.10.4 The effect of channel-substrate spacing

Increasing the channel substrate length reduce the backgating and decreases the substrate current. Also the TFL current is reduced with increasing this parameter.

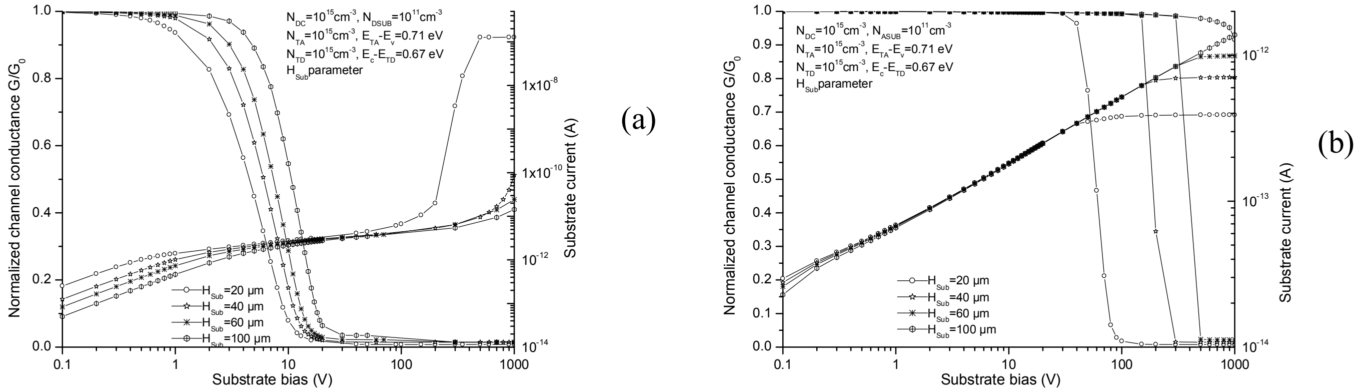


Fig 4.32 : channel-substrate spacing effect on backgating and substrate current in n15n11 (a) and n15p11 (b) structures.

4.10.5 The TFL current

Since the TFL current is more apparent in the structures nn$^-$ (good candidate of relaxation materials). Fig 4.33 illustrate the effect of substrate doping on TFL type.

In the structure when the channel has a doping density of $N_D=10^{15}$ cm^{-3} and the substrate has the doping density as variable parameter, figure 4.33.(a) shows that the TFL current appears better in the case where the substrate is more n-type. The same observation is given by fig 4.33.(b) where, in this case the channel has a doping density of $N_D=10^{16}$ cm^{-3} and the substrate is initially n-type.

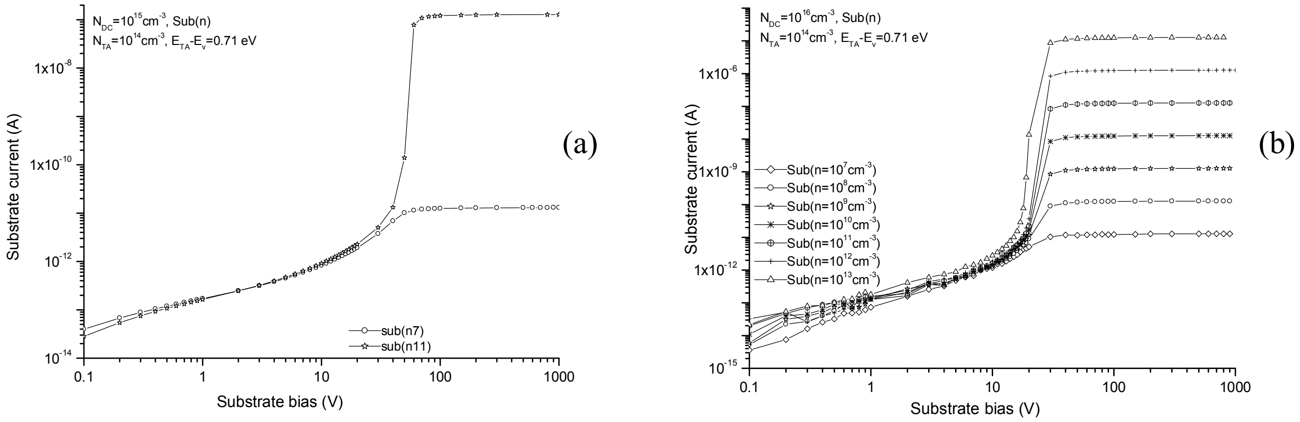


Fig 4.33: The effect of substrate doping on backgating and substrate current in: n15sub (n=7, 11) (a) and n16 sub (n =7, 8, 9, 10, 11, 12, 13) (b) structures.