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A Method of Determining the Recombination Centre Level in High-Speed Power Devices

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Abstract: Rational adjusting 3 main parameters of fast p^+nn^+ structure such as the forward voltage drop, reverse recovery time and reverse current means to control rationally the carrier lifetime of high and low level and the space-charge generation carrier lifetime. In other words, we should make the lifetime of the high-level carrier and the space charge generation carrier as long as possible but the low-level carrier lifetime as short as possible. The best way to satisfying these relations is forming the optimal recombination center level. In this paper, we analyze of optimal recombination center level to adjust rationally the 3 main parameters of fast p^+nn^+ structure - forward voltage drop, reverse recovery time and reverse current. Forward voltage drop of p^+nn^+ structure is affected strongly by the high-level carrier lifetime. Reverse current is affected strongly by the low-level lifetime and reverse recovery time is affected strongly by the space-charge generation lifetime. These 3 carrier lifetimes influence 3 main parameters of p^+nn^+ structure differently. When we decrease the low-level carrier lifetime in order to decrease the reverse recovery time, the forward voltage drop increases and when we increase the high-level carrier lifetime for reducing the forward voltage drop, the reverse recovery time increases**.** So, in order to adjust these conflicting relations, we will illuminate about the recombination center level formed in the basic floor of p^+nn^+ structure. On the other hand, to determine the recombination center level coincide with practical recombination center level, we suggest the analytic method of determination the recombination center level formed by 2 carrier lifetime regulation sources.

Keywords: Optimal Recombination Center Level, p^+nn^+ Structure, 3 Main Parameters, Analysis

1. Introduction

Rational adjusting 3 main parameters of fast p^+nn^+ structure such as the forward voltage drop, reverse recovery time and reverse current means to control rationally the carrier lifetime of high and low level and the space-charge generation carrier lifetime [3, 4, 11-18].

In other words, we should make the lifetime of the high-level carrier and the space charge generation carrier as long as possible but the low-level carrier lifetime as short as possible.

The best way to satisfying these relations is forming the optimal recombination center level [19-23].

In this paper, we suggest the main relative equations to determine the optimal recombination center level with the numerical solutions. Also, we found out the practical recombination center level which is irrelevant to the doping agent concentration and working temperature.

Next, we suggest the analytic method to determine the co-additive recombination center level coincident with the practical recombination center level by adding any 2 types of carrier lifetime regulation sources.

2. Analysis of the Optimal Recombination Center Level

To determine the optimal recombination center level for adjusting forward voltage drop, reverse recovery time and reverse current rationally, I introduce the following equation,

$$\eta = \frac{\tau_{HL}}{\tau_{LL}} \times \frac{\tau_{SC}}{\tau_{LL}} = f(E_{t,op}) \quad (1)$$

here

$$\frac{\tau_{HL}}{\tau_{LL}} = \frac{1+\xi}{1+exp\left(\frac{E_t-E_f}{KT}\right)+\xi exp\left(\frac{2E_i-E_t-E_f}{KT}\right)} \quad (2)$$

$$\frac{\tau_{SC}}{\tau_{LL}} = \frac{exp\left(\frac{E_t-E_i}{KT}\right)+\xi exp\left(\frac{E_i-E_t}{KT}\right)}{1+exp\left(\frac{E_t-E_f}{KT}\right)+\xi exp\left(\frac{2E_i-E_t-E_f}{KT}\right)} \quad (3)$$

$$E_f = 1.11 - KTln\left(\frac{n_0}{n_i}\right), \text{(Source: [7])}$$

$$n_i = 3.87 \times 10^{16} T^{3/2}\, e^{-7.02\times10^3/T}, \text{(Source: [8])}$$

$$\xi = 0.827\frac{\sigma_{cp}}{\sigma_{cn}}, \text{(Source: [9])}$$

σ_{cp} − Capture cross section of holes in the level of recombination,

σ_{cn} − Capture cross section of electrons in the level of recombination,

K, T − Statistical constant and absolute temperature,

E_i − Intrinsic energy level,

n_0 − Doping agent concentration,

E_f − Fermi- level.

In equation 1 τ_{HL}/τ_{LL} is the term that adjusts rationally the forward voltage drop and reverse recovery time in the fast semiconductor device [2]. And τ_{SC}/τ_{LL} is the term that adjusts rationally the reverse current and reverse recovery time in the fast semiconductor device [6].

Figure 1 shows the calculation result of the equation $\tau_{HL}/\tau_{LL} = f(E_t)|_{\substack{n_0=5\times10^{13}cm^{-3}\\T=400K}}$ with graph.

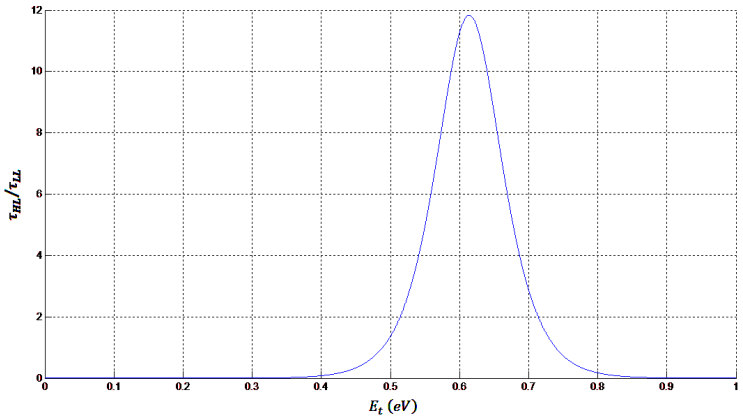


Figure 1. *Relative curve of* $\tau_{HL}/\tau_{LL} = f(E_t)|_{\substack{n_0=5\times10^{13}cm^{-3}\\T=400K}}$.

Figure 2 shows the calculation results with graph of $\tau_{SC}/\tau_{LL} = f(E_t)|_{\substack{n_0=5\times10^{13}cm^{-3}\\T=400K}}$.

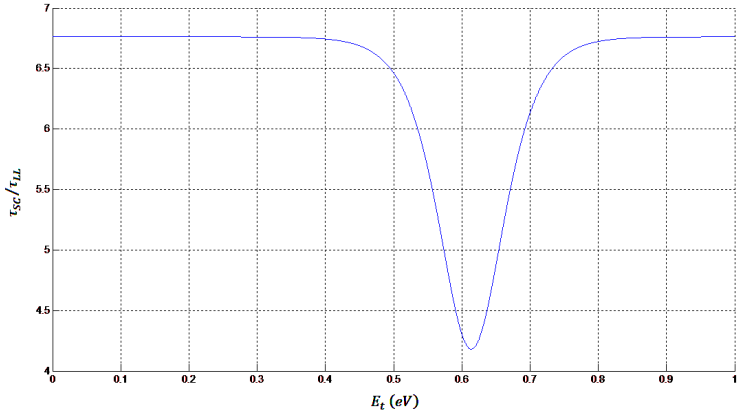


Figure 2. *Relative curve of* $\tau_{SC}/\tau_{LL} = f(E_t)|_{\substack{n_0=5\times10^{13}cm^{-3}\\T=400K}}$.

When we change the recombination center level E_t, the function $f(E_t) = \tau_{HL}/\tau_{LL}$. has the maximum value (Figure 1) and the function $f(E_t) = \tau_{SC}/\tau_{LL}$ has minimum value (Figure 2).

So, the value of η becomes maximum one at certain recombination center level and this recombination center level will become the optimal recombination center level-$E_{t,op}$.

In other words, the forward voltage drop, reverse recovery time and reverse current are adjusted rationally when the recombination center level equals to the value of $E_{t,op}$.

Figure 3 presents the calculation result with graph of $\eta = f(E_t)|_{\substack{n_0=5\times10^{13}cm^{-3}\\T=400K}}$.

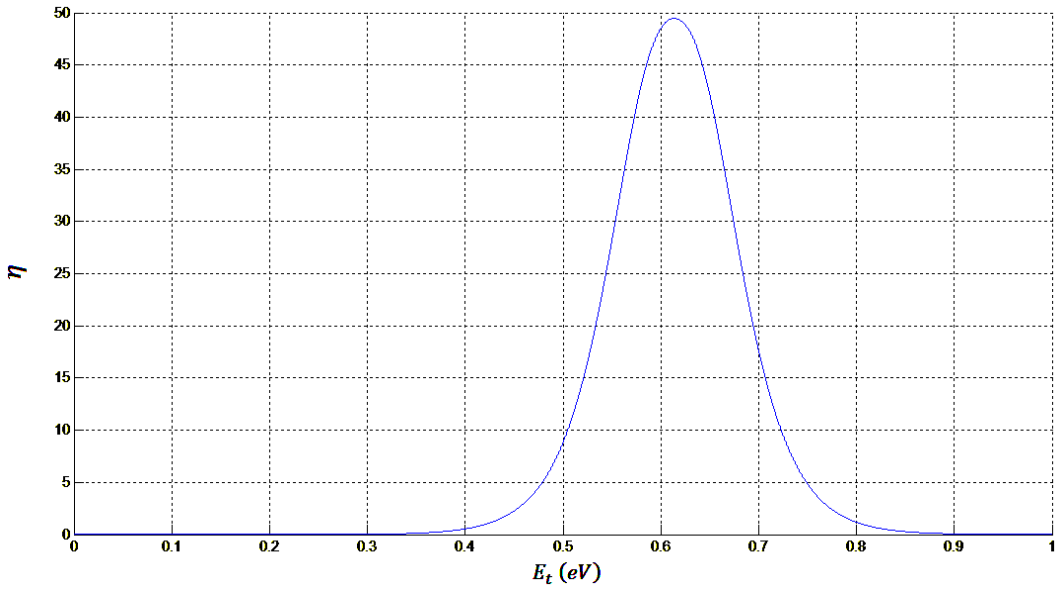


Figure 3. *Relative curve of* $\eta = f(E_t)|_{\substack{n_0=5\times10^{13}cm^{-3}\\ T=400K}}$.

As we can see in Figure 3, when $\xi = 30, T = 400K, n_0 = 5 \times 10^{13}cm^{-3}$, the optimal recombination center level - $E_{t,op}$ which adjust the most rationally 3 main parameters of p+nn+ structure exists and the value is 0.614eV. The optimal recombination center level $E_{t,op}$ is changed by doping agent concentration n_0, ratio of hole's caption cross section to electron's caption cross section ξ and working temperature T. From Figures 4 to 6 show the changes of $E_{t,op}$ depending on n_0, ξ, T with graph. Figure 4 shows the value of $E_{t,op}$ when the doping agent concentration n_0 is in the interval of 10^{13}~10^{16}cm^{-3} and the working temperature is the interval of 300 ~ 400K.

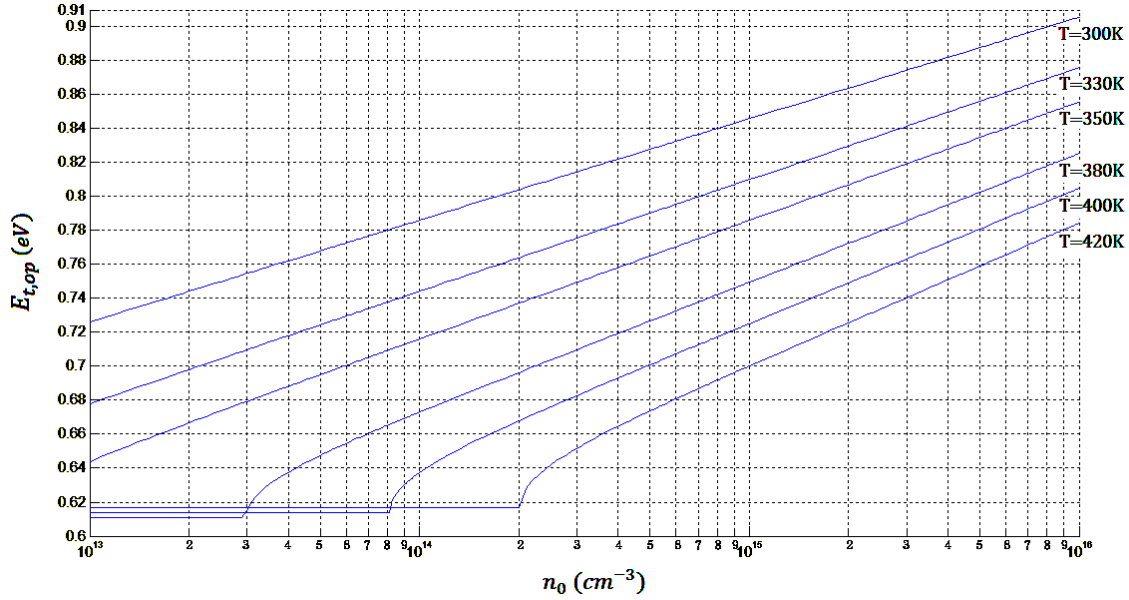
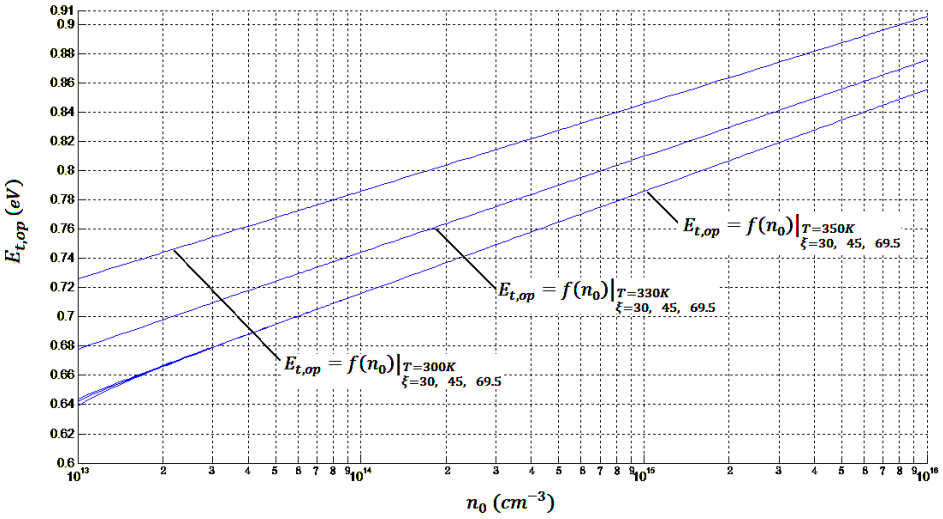


Figure 4. *Relative curve of* $E_{t,op} = f(n_0)\big|_{\substack{\xi=30\\ T=300\sim420K}}$.

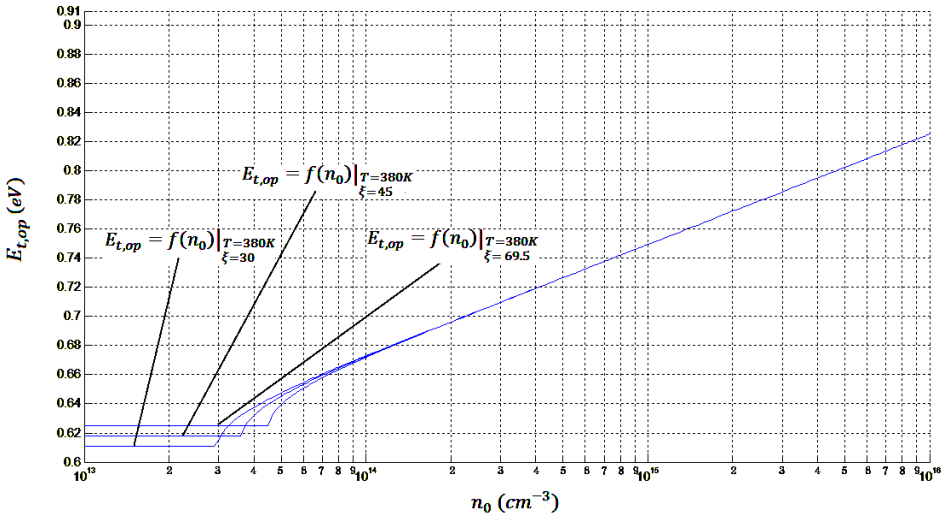
Analysis of curves showed in from Figures 1 to 4 like this.

When the doping agent concentration n_0 is in the interval of 10^{13}~10^{16}cm^{-3} and temperature T is in the interval of 300~400K, the optimal recombination center level $E_{t,op}$ exists.

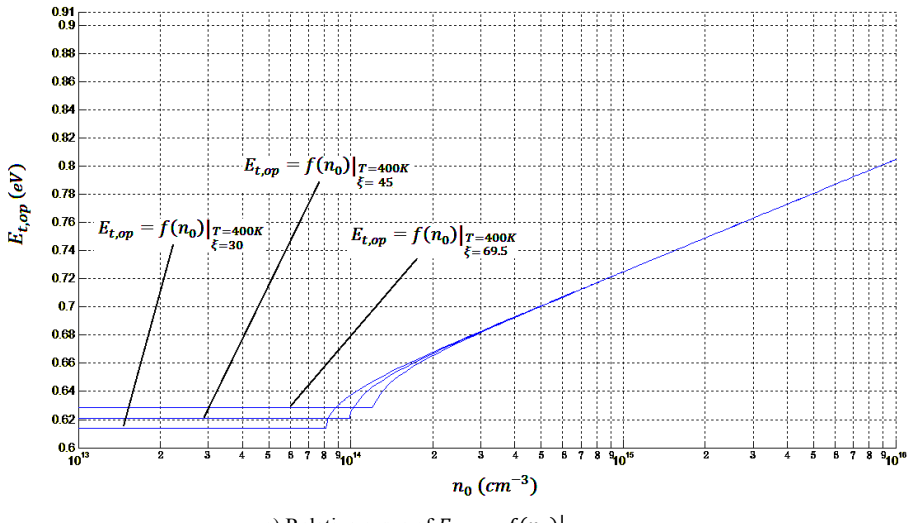
When doping agent concentration n_0 is increased, the optimal recombination center level $E_{t,op}$ is increased linearly. When temperature T is increased, the optimal recombination center level $E_{t,op}$ is decreased. When the temperature is high and the doping agent concentration n_0 is at below the certain value, $E_{t,op}$ doesn't change. Figure 5 shows the relative curve of $E_{t,op} = f(n_0)\big|_{\substack{\xi=30\\ T=300\sim420K}}$ in the different conditions of temperature. As we can see in Figure 5, the changes of $E_{t,op}$ depending on ξ are not so much in the wide interval of n_0 (10^{13}~$10^{16}cm^{-3}$).



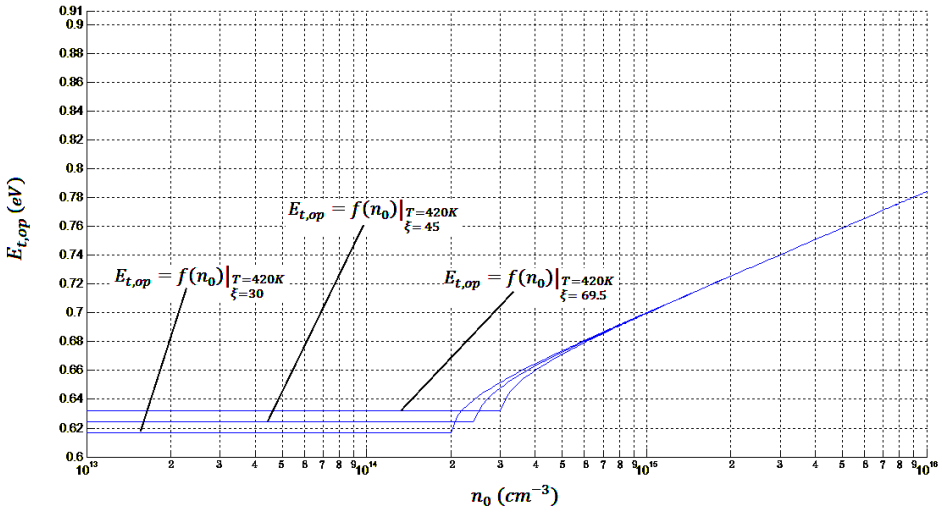
a) Relative curve of $E_{t,op} = f(n_0)|_{T=300,330,350K}$ ξ=30,45,69.5



b) Relative curve of $E_{t,op} = f(n_0)|_{T=380K}$ ξ=30,45,69.5



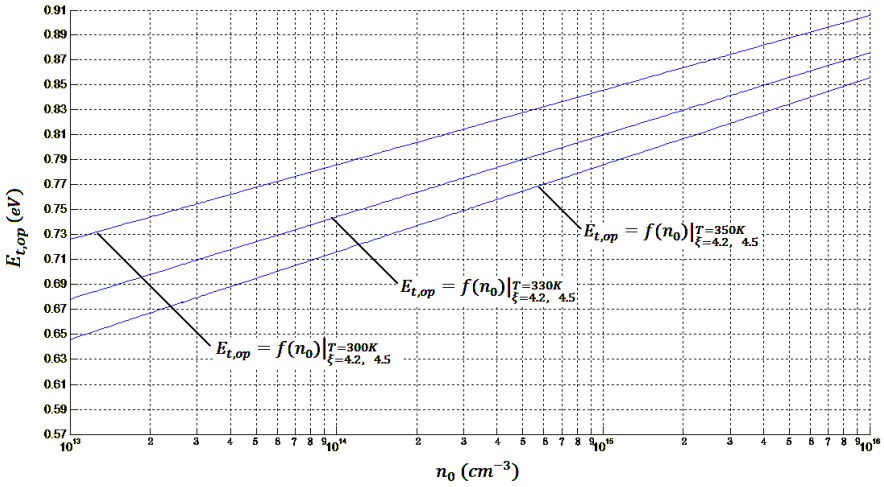
c) Relative curve of $E_{t,op} = f(n_0)|_{T=400K}$ ξ=30,45,69.5



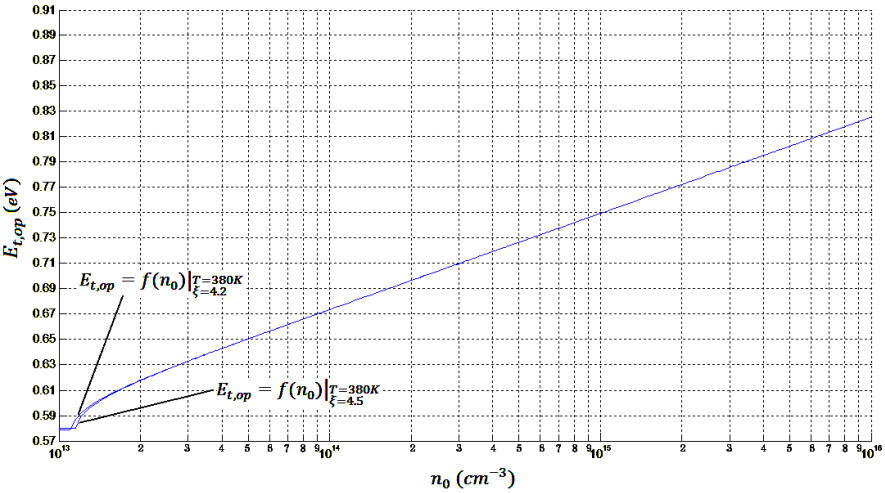
d) Relative curve of $E_{t,op} = f(n_0)\big|_{\xi=30,45,69.5}^{T=420K}$

Figure 5. *Relative curve of* $E_{t,op} = f(n_0)\big|_{\xi=30,45,69.5}$.

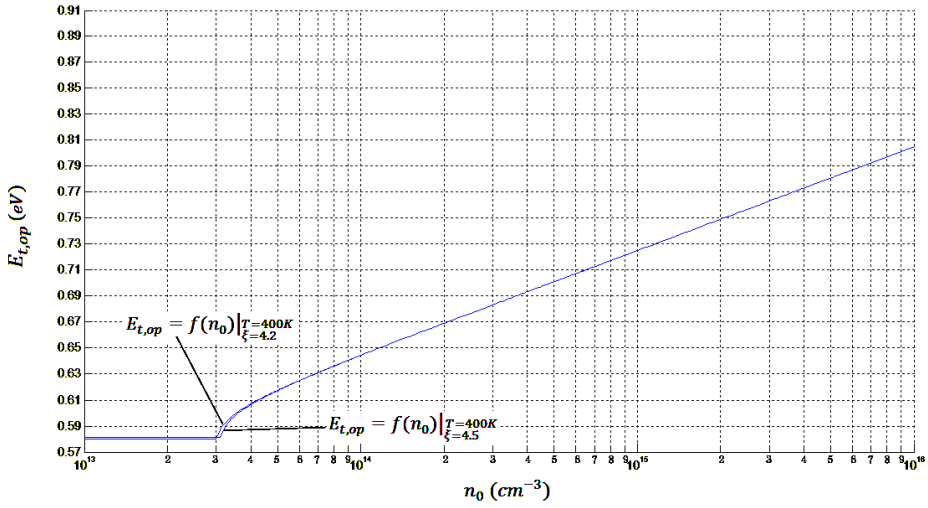
Figure 6 shows the relative curves of $E_{t,op} = f(n_0)\big|_{\xi=4.2,4.5}$ in the different temperature conditions. As you can see changes of $E_{t,op}$ are negligibly small in the wide interval of n_0 (10^{13}~10^{16}cm^{-3}). (Figure 6)



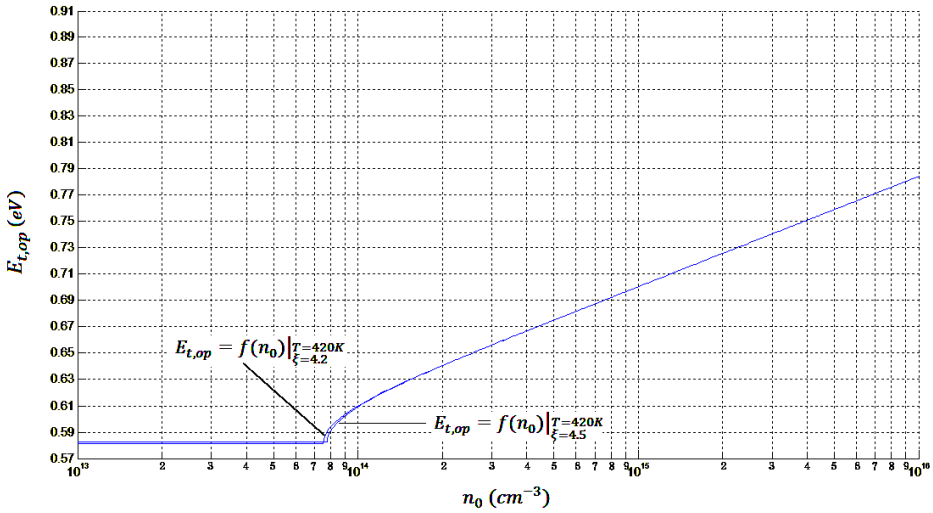
a) Relative curve of $E_{t,op} = f(n_0)\big|_{\xi=4.2,4.5}^{T=300,330,350K}$



b) Relative curve of $E_{t,op} = f(n_0)\big|_{\xi=4.2,4.5}^{T=380K}$



c) Relative curve of $E_{t,op} = f(n_0)\big|_{\xi=4.2,4.5}^{T=400K}$



d) Relative curve of $E_{t,op} = f(n_0)\big|_{\xi=4.2,4.5}^{T=420K}$

Figure 6. *Relative curve of* $E_{t,op} = f(n_0)\big|_{\xi=4.2,4.5}$

In the previous process, we analyzed the optional recombination levels $E_{t,op}$ that adjust rationally the main characteristics of the fast semiconductor device such as forward voltage drop, reverse recovery time and reverse current.

The optimal recombination center level $E_{t,op}$ is determined surely when we set the specific resistance of original material and working temperature of device. So in order to improve the characteristics of the fast semiconductor devices, we must choose the carrier lifetime regulation sources that the recombination center level is close to the $E_{t,op}$.

Now the sources of heavy metal impurity diffusion and radiation exposure are the sources of carrier lifetime controls which are widely used in order to improve the fast character of semiconductor devices. The gold, platinum and iridium are the sources of heavy metal impurity diffusion and the electronics wire, fast neutrons, γ −wire and protons are the sources of the radiation exposure.

When we manufacture the fast semiconductor devices with iridium diffusion, the main recombination center level E_{Ir} is $E_V + 0.83\text{eV}$ and ξ_{Ir} is 45.

The working temperature and doping agent concentration which satisfy the $E_{t,op} = E_{Ir} = E_V + 0.83\text{eV}$ when the $E_{Ir} = E_V + 0.83\text{eV}$ and $\xi_{Ir} = 45$ like this;

1) When T which is working temperature equals to $300K$, the doping agent concentration $n_0 = 6 \times 10^{14}\text{cm}^{-3}$.
2) When T which is working temperature equals to $330K$, the doping agent concentration $n_0 = 2 \times 10^{15}\text{cm}^{-3}$.
3) When T which is working temperature equals to $350K$, the doping agent concentration $n_0 = 4 \times 10^{15}\text{cm}^{-3}$.
4) In the doping agent concentration $n_0 \leq 10^{16}\text{cm}^{-3}$ the $E_{t,op}$ doesn't exist when the working temperature equals to $380K$.
5) In the doping agent concentration $n_0 \leq 10^{16}\text{cm}^{-3}$ the $E_{t,op}$ doesn't exist when the working temperature equals to $400K$.
6) In the doping agent concentration $n_0 \leq 10^{16}\text{cm}^{-3}$ the $E_{t,op}$ doesn't exist when the working temperature equals to $420K$.

Through the result of the former, we can know that the doping agent concentration should increase when the working temperature becomes higher in order to make the $E_{Ir} = E_v + 0.83\text{eV}$ when we diffuse the iridium. But, when the optimal recombination center level coincident with the recombination center level formed by diffusing iridium, the doping agent concentration n_0 is bigger or equal than $6 \times 10^{14}\text{cm}^{-3}$ in the temperature interval of $300\text{K} \leq \text{T} \leq 420\text{K}$.

Next, when we manufacture the fast semiconductor device with the gold diffusion, the main recombination center level formed in the silicon material E_{Au} is $E_V + 0.57\text{eV}$ and ξ_{Au} equals to 69.5.

When E_{Au} equals to $E_V + 0.57\text{eV}$ and ξ_{Au} equals to 69.5, the working temperature and doping agent, that satisfy the $E_{t,op} = E_{Au}$, doesn't exist in the interval of $300K \leq T \leq 420K$ and $10^{13}cm^{-3} \leq n_0 \leq 10^{16}cm^{-3}$ (figure 5).

This shows that when we manufacture the fast semiconductor devices with gold diffusion, they aren't adequate to adjust rationally the main characteristics of this one.

When we make the fast semiconductor device with the iridium diffusion, the main recombination center level formed in the silicon material E_{Pt} equals to $E_V + 0.42\text{eV}$ and ξ_{Pt} equals to 4.2.

When E_{Pt} is $E_V + 0.42\text{eV}$, ξ_{Pt} equals to 4.2, the working temperature and doping agent concentration, that satisfy $E_{t,op} = E_{Pt} = E_V + 0.42\text{eV}$ and $\xi_{Pt} = 4.2$, don't exist in the interval of $300\text{K} \leq \text{T} \leq 420\text{K}$, $10^{13}\text{cm}^{-3} \leq n_0 \leq 10^{16}\text{cm}^{-3}$. (figure 6)

This shows that when we manufacture the fast semiconductor devices with the platinum diffusion, they aren't adequate to adjust rationally the 3 main characteristics of this one.

From the relations among the recombination center level, which is formed by the different kinds of carrier lifetime regulation sources, and doping agent concentration of original material and temperature, we got the following result;

1) The recombination center levels formed by the different kinds of carrier lifetime regulation sources should satisfy the doping agent concentration and temperature conditions of original material in order to coincident with the optimal recombination center level or close to there.
2) As we can see in Figure 4, in the definite ranges n_0 and T, the optimal recombination center level doesn't change. The optimal recombination center level $E_{t,op}$ is irrelevant to the definite intervals of the temperature and doping agent concentration, so the real significance is great and we call this practice recombination center level E_t^*.
3) When $\xi = 30, 45, 69.5$, the changes of practical recombination center level $-E_t^*$ aren't great in the definite interval of working temperature and doping agent concentration.
4) When $\xi = 4.2, 4.5$ we can irrelevant the change of $E_t^* -$ the practical recombination center level in the definite interval of working temperature and doping agent concentration.
5) When $\xi \geq 30$, the practical recombination center level exists in the case of $T > 361K$ (figure 5). But when $\xi \leq 4.5$, the practical recombination center level exists in the case of the $T > 379K$(Figure 5).

3. Analysis of Co-additive Recombination Center Level Coincident

The solution to form with the recombination center level coincident with the practical recombination center level is to co-add 2 carrier lifetime control sources.

We introduce the analytic method that calculates the recombination center level formed in the silicon semiconductor material added the gold and iridium at the same time. Generally, when the gold and iridium are added at the same time, the carrier lifetime τ_Σ like this [5, 10]:

$$\tau_\Sigma{}^{-1} = \tau_{Ir}{}^{-1} + \tau_{Au}{}^{-1} \tag{4}$$

Here τ_{Ir} – Carrier lifetime when iridium added, τ_{Au} –Carrier lifetime when gold added.

In the case of having a co-additive recombination center level when we consider the charge neutral condition $\Delta n = \Delta p$ in n-type semiconductor, we can express as following according to the Shockley-Read-Hall (SRH) statistics [1].

$$\tau_\Sigma = (\tau_{p0})_\Sigma \left[1 + \frac{1}{1+h}\exp\left(\frac{E_{t,\Sigma} - E_{f,\Sigma}}{KT}\right)\right] + (\tau_{n0})_\Sigma \left[\frac{h}{1+h} + \frac{1}{1+h}\exp\left(\frac{2E_i - E_{t,\Sigma} - E_{f,\Sigma}}{KT}\right)\right] \tag{5}$$

Here $E_{f,\Sigma} -$ Fermi-level after co-additive,

$h = \frac{n_0}{\Delta n} -$ Injection level ($\Delta n -$excess charge carrier concentration, $n_0 -$doping agent concentration),

$K -$Satisfical constant,

$T -$Absolute temperature.

Considering equation 5, the carrier lifetime expresses like this when the iridium diffuses to the silicon semiconductor material.

$$\tau_{Ir} = \tau_{p0}^{Ir}\left[1 + \frac{1}{1+h}\exp\left(\frac{E_{t,Ir} - E_{f,Ir}}{KT}\right)\right] + \tau_{n0}^{Ir}\left[\frac{h}{1+h} + \frac{1}{1+h}\exp\left(\frac{2E_i - E_{t,Ir} - E_{f,Ir}}{KT}\right)\right] \tag{6}$$

When the gold diffuse to the silicon semiconductor material, the carrier lifetime is expressed as following according to the equation 5;

$$\tau_{Au} = \tau_{p0}^{Au}\left[1 + \frac{1}{1+h}exp\left(\frac{E_{t,Au} - E_{f,Au}}{KT}\right)\right] + \tau_{n0}^{Au}\left[\frac{h}{1+h} + \frac{1}{1+h}exp\left(\frac{2E_i - E_{t,Au} - E_{f,Au}}{KT}\right)\right] \tag{7}$$

Here $\tau_{p0}^{Ir}, \tau_{n0}^{Ir}$ − Lifetime of hole and electron when iridium added,
$\tau_{p0}^{Au}, \tau_{n0}^{Au}$ − Lifetime of hole and electron when gold added,
$E_{f,Ir}$ – Fermi-level when iridium added,
$E_{f,Au}$ − Fermi-level when gold added.
Substituting equation 5 and 6 for equation 4 we can get the result like this;

$$\tau_{\Sigma}{}^{-1} = \left\{\tau_{p0}^{Ir}\left[1+\frac{1}{1+h}exp\left(\frac{E_{t,Ir}-E_{f,Ir}}{KT}\right)\right]+\tau_{n0}^{Ir}\left[\frac{h}{1+h}+\frac{1}{1+h}exp\left(\frac{2E_i-E_{t,Ir}-E_{f,Ir}}{KT}\right)\right]\right\}^{-1}+\left\{\tau_{p0}^{Au}\left[1+\frac{1}{1+h}exp\left(\frac{E_{t,Au}-E_{f,Au}}{KT}\right)\right]+\tau_{n0}^{Au}\left[\frac{h}{1+h}+\frac{1}{1+h}exp\left(\frac{2E_i-E_{t,Au}-E_{f,Au}}{KT}\right)\right]\right\}^{-1} \quad (8)$$

We can express the $\tau_{p0}^{Ir}, \tau_{n0}^{Ir}, \tau_{p0}^{Au}, \tau_{n0}^{Au}$ like these;

$$\tau_{p0}^{Ir} = \frac{1}{V_{Tp}\sigma_{p0}^{Ir}N_t^{Ir}} \quad (9)$$

$$\tau_{n0}^{Ir} = \frac{1}{V_{Tn}\sigma_{n0}^{Ir}N_t^{Ir}} \quad (10)$$

$$\tau_{p0}^{Au} = \frac{1}{V_{Tp}\sigma_{p0}^{Au}N_t^{Au}} \quad (11)$$

$$\tau_{n0}^{Au} = \frac{1}{V_{Tn}\sigma_{n0}^{Au}N_t^{Au}} \quad (12)$$

Here V_{Tn}, V_{Tp} − Heat movement velocity of electron and hole,
$\sigma_{p0}^{Ir}, \sigma_{n0}^{Ir}$ − Capture cross section of electron and hole of iridium,
$\sigma_{p0}^{Au}, \sigma_{n0}^{Au}$ − Capture cross section of electron and hole of gold,
N_t^{Ir}, N_t^{Au} − Concentration of iridium and gold.
The equation for numerical calculating $E_{f,Ir}$ like this;

$$N_t exp\left(\frac{E_{f,Ir}-E_c}{KT}\right)+N_t^{Ir}\left[1+2exp\left(\frac{E_A^{Ir}-E_{f,Ir}}{KT}\right)+exp\left(\frac{E_D^{Ir}+E_A^{Ir}-2E_{f,Ir}}{KT}\right)\right]^{-1} = N_V exp\left(\frac{E_V-E_{f,Ir}}{KT}\right)+N_D\left[1+exp\left(\frac{E_V-E_D}{KT}\right)\right]^{-1}+N_t^{Ir}\left[1+2exp\left(\frac{E_{f,Ir}-E_D^{Ir}}{KT}\right)+exp\left(\frac{2E_{f,Ir}-E_D^{Ir}-E_A^{Ir}}{KT}\right)\right]^{-1} \quad (13)$$

Next, the equation for numerical calculating $E_{f,Au}$ like this;

$$N_t exp\left(\frac{E_{f,Au}-E_c}{KT}\right)+N_t^{Au}\left[1+2exp\left(\frac{E_A^{Au}-E_{f,Au}}{KT}\right)+exp\left(\frac{E_D^{Au}+E_A^{Au}-2E_{f,Au}}{KT}\right)\right]^{-1} = N_V exp\left(\frac{E_V-E_{f,Au}}{KT}\right)+N_D\left[1+exp\left(\frac{E_V-E_D}{KT}\right)\right]^{-1}+N_t^{Au}\left[1+2exp\left(\frac{E_{f,Au}-E_D^{Au}}{KT}\right)+exp\left(\frac{2E_{f,Au}-E_D^{Au}-E_D^{Au}}{KT}\right)\right]^{-1} \quad (14)$$

Here, N_C − State concentration of conduction band,
N_V − State concentration of valence band,
E_D^{Ir}, E_A^{Ir} −Acceptor-level and donor level of iridium,
E_D^{Au}, E_I^{Au} −Acceptor-level and donor level of gold,
E_C, E_V − Level of conduction band and valence band,
E_D, − Doping agent concentration.
The co-additive recombination center level $E_{t,\Sigma}$ is calculated as following;

1) According to the equation 13, we can get the Fermi level $E_{f,Ir}$ in the case of diffusing the iridium.
2) According to the equation 14, we can get the Fermi level $E_{f,Au}$ in the case of diffusing the gold.
3) When we get the $E_{f,Ir}$ and $E_{f,Au}$, we must get $\tau_{p0}^{Ir}, \tau_{n0}^{Ir}, \tau_{p0}^{Au}, \tau_{n0}^{Au}$ by substituting the N_t^{Ir}, N_t^{Au} (which are already chosen by us) for the equation 9 ~12.
4) According to the equations 6 and 7, we can get the τ_{Ir}, τ_{Au} and calculate τ_{Σ} by substituting these values for equation 4.
5) Substitute the values of τ_{Σ} for the equation 5 and get $E_{t,\Sigma}$.

The co-additive recombination center level $E_{t,\Sigma}$ is the important parameter that decides the recombination characters in the silicon semiconductor material when gold and iridium are added at the same time.

With this method, we can decide the co-additive recombination center level when we add the random 2 carrier lifetime control sources.

When we add gold and iridium at the same time, the co-additive recombination center level $E_{t,\Sigma}$ equals to $E_V + 0.57\text{eV}$.

When we add gold and iridium at the same time, the practical recombination center level locates $E_V + 0.61\text{eV} \leq E_t^* \leq E_V + 0.617\text{eV}$ in the intervals of working temperature $380\text{K} \leq \text{T} \leq 420\text{K}$.

So the co-additive recombination center level $E_{t,\Sigma}$ locates close to the practical recombination center level E_t^*

As a result, when we co-add the gold and iridium, 3 main parameters of fast diode are adjusted rationally in the intervals of working temperature T=380~400K.

This method can be adapted to the rational regulation of

the 3 parameters of fast diode in the random doping agent concentration and co-additive concentration and the other intervals of working temperature.

4. Conclusions

We set and analysis the optimal recombination center level to adjust the 3 main parameters of fast diode rationally. In this course, I illuminated that the practical recombination center level E_t^* exists and different kinds of factors affect to E_t^*. Also, we found analytic method to determine the co-additive recombination center level $E_{t,\Sigma}$ formed in the silicon semiconductor material added 2 carrier lifetime control sources at the same time and proved the possibility that co-additive recombination center level locates close to practical recombination center level using this method.

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