IMPACT OF THE TEST SIGNAL FREQUENCY ON CAPACITANCE-VOLTAGE CHARACTERISTICS OF THE METAL-SEMICONDUCTOR CONTACT WITH DEEP LEVELS INSIDE THE STRUCTURE

V.V. Ilchenko, O.Yu. Kondratovich, O.V. Tretyak, M.V. Shkil
Kyiv National Taras Shevchenko University, 64,Volodymyrska str., Kyiv, Ukraine 01033
Phone: +38-044-209-44-90 E-mail: ilch@uninet.kiev.ua

1. Introduction

In the last years the growing of self-organized quantum dots in group IV materials system and investigation of their properties draws more and more attention of scientists and technologists due to possibility of creation of new functioning devices of microelectronics [1-2]. The goal of the work is working out the theory for obtaining the voltage-capacitance dependence of the semiconductor structure with impurity deep levels in it taking into consideration the frequency of a small-amplitude ac voltage.

2. Calculation

While considering the equivalent scheme of the contact let us assume that a p-type semiconductor in addition to the doping concentration p_0 has a deep acceptor level with the concentration p_1 (Fig.1).

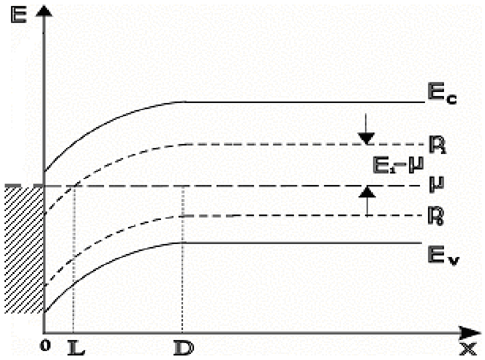

Fig. 1. Metal-semiconductor contact with shallow and deep levels

Let us apply an electric voltage modulated with some frequency ω to the contact (Fig. 2). U_0 is the level of a consistent voltage. ΔU_0 is a double amplitude of the voltage variable part.

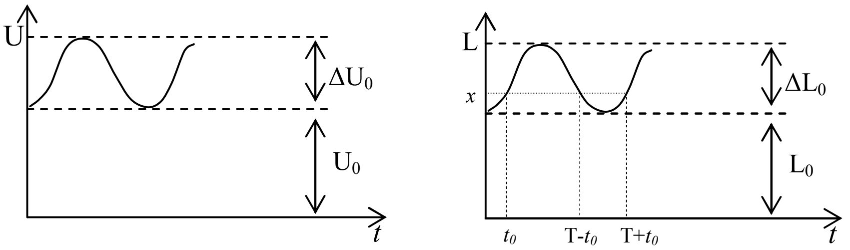

Fig. 2. Dependence of voltage applied to metal-semiconductor contact and layer thickness L where all deep impurities are emitted on time

A variable part of the whole charge at deep levels can be calculated with the following equation:

$$Q(t) = \int\limits_{L_0}^{L_0+\Delta L_0} p(x,t)dx \tag{1}$$

As time passes the concentration of emitted holes in each position of the layer ΔL_0 changes with exponential law from some minimum value $p_{\min}(x)$ to some maximum value $p_{\max}(x)$ and in the opposite direction depending on the value ΔL at a given moment of time. If $x < \Delta L$, the process of holes emission takes place, otherwise if $x > \Delta L$, the process of holes capture takes place. So

$$p(x,t) = \begin{cases} p - (p - p_{\min}(x))e^{-\frac{t-t_0(x)}{\tau}}, t_0(x) < t < T - t_0(x) \\ p_{\max}(x)e^{-\frac{t-T+t_0(x)}{\tau}}, T - t_0(x) < t < T + t_0(x) \end{cases} \tag{2}$$

where τ is a hole emission time from deep levels, $t_0(x)$ is a start moment of holes emission in the position with a coordinate x, T is an oscillation period: $t_0(x) = \frac{\arccos\left(1 - \frac{2x}{\Delta L_0}\right)}{\omega}$, $T = {}^{2\pi}\!/_{\omega}$. From Eq.(2) we can find $p_{\min}(x)$ and $p_{\max}(x)$ by writing *p(x,t)* for *$t=T-t_0(x)$* and *$t=T+t_0(x)$*, $p_{\min}(x) = p_{\max}(x)e^{-\frac{2t_0(x)}{\tau}}$ and $p_{\max}(x) = p\frac{1-e^{-\frac{T-2t_0(x)}{\tau}}}{1-e^{-\frac{T}{\tau}}}$.

Let us fix a certain moment of time t and calculate for it the charge Q(t) using Eq.(1):

$$Q(t) = \int\limits_{0}^{\frac{\Delta L_0}{2}(1-\cos(\omega t))} \left[p - [p - p_{\min}(x)]e^{-\frac{t-t_0(x)}{\tau}} \right] dx + \int\limits_{\frac{\Delta L_0}{2}(1-\cos(\omega t))}^{\Delta L_0} p_{\max}(x)e^{-\frac{t-T+t_0(x)}{\tau}} dx \tag{3}$$

Then Eq.(3) can be written as:

$$Q(t) = \begin{cases} \int\limits_{0}^{\frac{2\Delta L_0}{T}t} \left[p - [p - p_{\min}(x)]e^{-\frac{t-t_0(x)}{\tau}} \right] dx + \int\limits_{\frac{2\Delta L_0}{T}t}^{\Delta L_0} p_{\max}(x)e^{-\frac{t+t_0(x)}{\tau}} dx, 0 \le t \le \frac{T}{2} \\ \int\limits_{0}^{2\Delta L_0\left(1-\frac{t}{T}\right)} \left[p - [p - p_{\min}(x)]e^{-\frac{t-t_0(x)}{\tau}} \right] dx + \int\limits_{2\Delta L_0\left(1-\frac{t}{T}\right)}^{\Delta L_0} p_{\max}(x)e^{-\frac{t-T+t_0(x)}{\tau}} dx, \frac{T}{2} \le t \le T \end{cases} \tag{4}$$

Calculating Eq.(4) everyone can obtain:

$$Q(t) = \begin{cases} \frac{2p\Delta L_0}{T}\left(t - \tau + \frac{2\tau e^{-\frac{t}{\tau}}}{1 + e^{-\frac{T}{2\tau}}} \right), 0 \le t \le \frac{T}{2} \\ \frac{2p\Delta L_0}{T}\left(T - t - \tau + \frac{2\tau e^{\frac{T}{2\tau}}}{1 + e^{-\frac{T}{2\tau}}} e^{-\frac{t}{\tau}} \right), \frac{T}{2} \le t \le T \end{cases} \tag{5}$$

A variable part of capacitance of semiconductor space charge area can be determining using the following equation:

$$C(t)=\frac{dQ(t)}{dV}=\frac{dQ(t)}{dt}\frac{dt}{d(\Delta L)}\frac{d(\Delta L)}{dV}=\frac{dQ(t)}{dt}\frac{dt}{d(\Delta L)}\frac{dD}{dV} \tag{6}$$

So we can write finally:

$$C(t)=\begin{cases} p\left(1-\dfrac{2e^{-\frac{t}{\tau}}}{1+e^{-\frac{T}{2\tau}}}\right)\dfrac{dD}{dV}, 0\le t\le\dfrac{T}{2} \\ p\left(1-\dfrac{2e^{\frac{T}{2\tau}}}{1+e^{-\frac{T}{2\tau}}}e^{-\frac{t}{\tau}}\right)\dfrac{dD}{dV}, \dfrac{T}{2}\le t\le T \end{cases} \tag{7}$$

An average meaning of the variable part of capacitance of a semiconductor space-charge region for the period T can be found using the following equation:

$$<C(t)>=\frac{1}{T}\int_0^T C(t)dt=p\left(1-\frac{th\left(\frac{T}{4\tau}\right)}{\frac{T}{4\tau}}\right)\frac{dD}{dV} \tag{8}$$

Finally, equation for the capacitance of the semiconductor structure with shallow and deep acceptor impurities will take the following form:

$$C=-\frac{e\sqrt{\varepsilon\varepsilon_0\left(p_0+p_1\left(1-\frac{th\left(\frac{T}{4\tau}\right)}{\frac{T}{4\tau}}\right)\right)}}{\sqrt{2\left(\varphi_0-\frac{E_1-\mu}{p_0+p_1}p_1-eV\right)}}, \tag{9}$$

where p_0 is the concentration of shallow acceptor impurities, p_1 is the concentration of deep acceptor impurities, τ is the hole emission time from deep levels, T is the period of the test voltage, μ is the Fermi energy, φ_0 is the zero-biased barrier height and E_1 is the energetic position of the deep level.

3. Conclusions

To obtain the capacitance-voltage dependencies the model of calculation of the deep level charge taking into consideration the deep acceptor impurity emission time and the frequency of the small-amplitude ac test voltage has been proposed. Received expression can be used for analysis of experimental C-V curves measured on low or transient frequencies when deep level recharge influence becomes remarkable. Moreover suggested equations for the capacitance can be used for the treatment measured addmitance data on different frequencies and to calculate from an experiment some parameters concerned with energetic position of deep levels(in quantum dots, for example) in the investigated structures.

4. References

[1] A.V.Dvurechenskii, A.I.Yakimov. FTP, 35, *9*, 1143 (2001).

[2] C.Miesner, T.Asperger, K.Brunner, and G.Abstreiter. *Appl. Phys. Lett.*, 77, *17*, 2704 (2000).