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PRESSURE EFFECTS ON THE SEMICONDUCTOR STRUCTURE PARAMETERS

Pressure effects on semiconductor structures are presented. Theoretical dependency of those effects on semiconductor structures electrophysical parameters is defined.

Key words: *pressure, deformation, sensors, semiconductor.*

Introduction

Vigorous development of sensors differentiated by structure and properties is related to the automation of control systems, various technological processes monitoring. Research works aimed to create such sensors in order to improve their key parameters: sensitivity, linearity, stability, efficiency boosting; response time and size reducing; integration with microprocessor means of processing measuring data efficiency.

This work deals with deformation results in the semiconductor structures under pressure. Theoretical dependency of effects on semiconductor structures electrophysical parameters is determined. Behavior of semiconductor devices under pressure may be simulated employing these dependencies.

Theoretical study

Semiconductor energy levels shifts [1, 2] as well as effective mass and charge carrier mobility changes [3, 4] represent the main electrophysical parameters changing under pressure. Charge carriers lifetime in extrinsic semiconductors is weakly dependent on pressure [3].

Semiconductor deformation under pressure results in bottom of conduction band and valence band apex shift in compliance with boundaries splitting. Changes in valence band positions ΔEv and splitting of its apex under pressure are defined by such statement [5]:

$$\Delta E_v(P) = a\Delta \pm \sqrt{\Omega_\varepsilon}\,, \tag{1}$$

where

$$\Omega_\varepsilon = b^2\left[\left(\varepsilon_{11}-\varepsilon_{22}\right)^2+\left(\varepsilon_{22}-\varepsilon_{33}\right)^2+\left(\varepsilon_{33}-\varepsilon_{11}\right)^2\right]+d^2\left(\varepsilon_{12}{}^2+\varepsilon_{13}{}^2+\varepsilon_{23}{}^2\right), \tag{2}$$

a, *b*, *d* – deformation potential of the valence band constants; Δ – semiconductor material capacity changes under pressure.

$$\Delta = \varepsilon_{11}+\varepsilon_{22}+\varepsilon_{33}\,, \tag{3}$$

where εij – strain tensor components.

Changes of valence band positions thereof deformation shift and its splitting under pressure may be described in general by such statement:

$$\Delta E_{ci}(P) = \Xi_d\Delta + \Xi_u\varepsilon_{ii}\,, \tag{4}$$

where Ξ_d and Ξ_u – deformation potential of the valence band constants; index i = 1, 2, 3 (index i = 1 corresponds to energy minimum values, in the direction of <100> and reversed to it, similarly i = 2 and i = 3 indices– directions <010> and <001> and reversed).

Changes in valence band positions and splitting of its apex under pressure due to deformation shift are described by general expression:

$$\Delta E_{ci}(P) = \Xi_d\Delta + \Xi_u\varepsilon_{ii} + \Delta E/4 - 2\,|\,\Xi_u\varepsilon_{jj}\,|\,, \tag{5}$$

де ΔE – difference between low levels without pressure; Ξ_u – deformation potential constant, which characterizes deformation shift effect; $f \neq j \neq i$ – indices (f = 1, 2, 3).

Effective width of prohibited zone in the strained semiconductor $E_g(P)$ is being estimated as the distance between the nearest levels of the splitted valence bands and conduction band. Amount of change under pressure $\Delta E_g(P)$ is [4]:

$$\Delta E_g(P) = \Delta E_c(P) - \Delta E_v(P), \tag{6}$$

where $\Delta E_v(P)$ – valence band level shift, which is the upper one due to the deformation under pressure; $\Delta E_c(P)$ – conduction band minimum value shift, which is inferior.

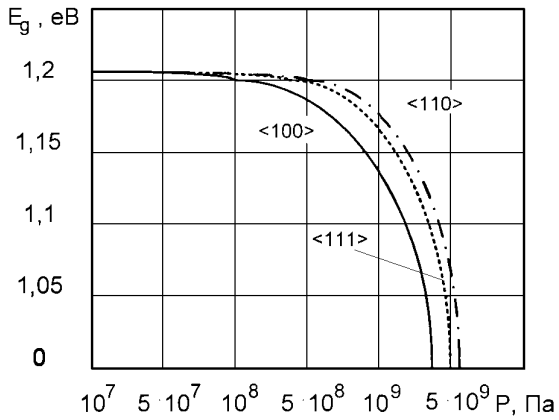

Fig. 1. Pressure dependency of prohibited band width

When pressure values are high enough (P>10^7 Pa for silicon) electron flow is taking place only at the bottom minimums of conductivity bands, therefore electron's effective mass remains de facto constant. Effective mass values of electron holes at the high pressure are stipulated by effective masses of the upper valence band levels under the condition of true inequality $\Delta E_v >> E(k)$, where $E(k)$ – charge carriers energy in the unstrained semiconductor. Under this condition effective masses of holes for silicon are $m_{||}/m_0 = 0{,}31$, $m^{\perp}/m_0 = 0{,}21$.

For little pressure (P<10^7 Pa for silicon) all energy minimums are participating in the process of conductance, therefore charge carriers mobility changes as the function of pressure[3]: this dependency doesn't exist when the pressure is high and all semiconductor device features then defined by fundamental minority carriers concentration $N_{minor}(n_p, p_n)$, pure charge carriers concentration n_i and pressure dependency.

Prohibited band width under pressure $\Delta E_g(P)$ is evaluated by expression (6), then carriers' concentration in pure semiconductor is [3]:

$$n_i(P) = n_{i0} \exp\left[-\Delta E_g(P) / kT\right], \tag{7}$$

where n_{i0} – charge carriers concentration in pure unstrained semiconductor.

Deformation increment Δn_i is evaluated as:

$$\Delta n_i(P) = n_{i0}\left(\exp\left[-\Delta E_g(P) / kT\right] - 1\right). \tag{8}$$

Charge carriers concentration under pressure in the n-conductivity zone with n-type impurity $N_D >> n_i$ is equal to [3]:

$$n_n(P) = N_D + {n_{i0}}^2 / N_D \exp\left[-\Delta E_g(P) / kT\right], \tag{9}$$

$$p_n(P) = {n_{i0}}^2 / N_D \exp\left[-\Delta E_g(P) / kT\right]. \tag{10}$$

Thereof deformation $n_n(0) = N_D + {n_{i0}}^2/N_D$ та $p_n(0) = {n_{i0}}^2/N_D$, then deformation increments of concentration values n_n and p_n are defines by the general rule:

$$\Delta n_n(P) = \Delta p_n(P) = {n_{i0}}^2 / N_D \left(\exp\left[-\Delta E_g(P)/kT\right]-1\right). \quad (11)$$

By analogy charge carriers concentration in the n-conductivity zone with n-type impurity ($N_A >> n_i$) under pressure is:

$$p_p(P) = N_A + {n_{i0}}^2 / N_A \exp\left[-\Delta E_g(P)/kT\right], \quad (12)$$

$$n_p(P) = {n_{i0}}^2 / N_A \exp\left[-\Delta E_g(P)/kT\right]. \quad (13)$$

Deformation increments of concentration values n_p and electron holes p_p are evaluated by the general expression:

$$\Delta p_p(P) = \Delta n_p(P) = {n_{i0}}^2 / N_A \left(\exp\left[-\Delta E_g(P)/kT\right]-1\right). \quad (14)$$

Fig. 2 represents silicon bipolar transistor's structure majority and minority charge carriers of p- and n-zones concentrations pressure dependency.

Mobility changes under little pressure are related to piezoresistive effect and it's more complex under high pressure. Mobility change is usually related to the compliant charge carrier mass change [3]. Every permanent energy ellipsoid is described with two different masses – along the ellipsoid axis $m\|$ and perpendicular to it $m^{\perp}$. There are various mobilities in compliance with that: along the axis $\mu\|$ perpendicular to the $\mu^{\perp}$ axis. Interlevel charge redistribution under the deformation leads to the two of these components' contribution to general mobility changes relative to unstrained semiconductor.

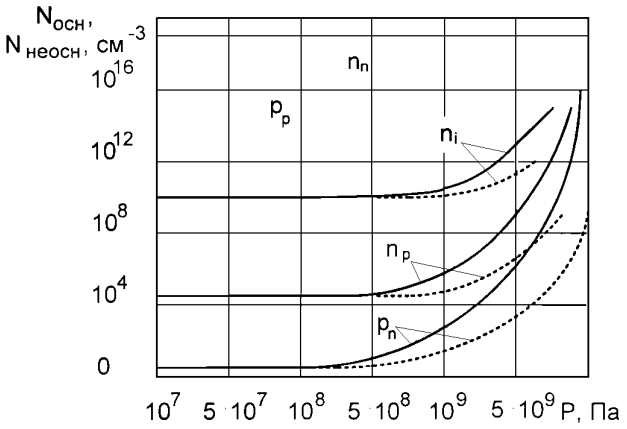

Fig. 2. Charge carriers concentration depending on pressure effects in the directions —— – <100> and- - - - – <111>

Electron's effective mobility is:

$$\mu_n = \sum_{i=1}^{N} \frac{n_{pi}}{n_p} \mu_i, \quad (15)$$

where μ_i – electron mobility on i-minimum along the current direction. μ_i value is expressed by $\mu\|$ and $\mu^{\perp}$.

Valleys of <010> та <001> in the <100> direction obtain the mobility of $\mu^{\perp}$, and <100> valley– $\mu\|$ mobility. Thus, in the unstrained semiconductor (silicon) with p-conductivity electron mobility along the crystallographic axis <100> is [6]:

$$\Delta\mu_{n0} = \frac{1}{3}\mu_{\|} + \frac{2}{3}\mu_{\perp}. \quad (16)$$

Different valleys contribution and electrons mobility deformation increment changes reckoning conversions conducted on the basis of (13), (15) and (16) expressions are following:

$$\Delta\mu_n(P) = \mu_{no}\left[\frac{\left(1+2K\exp\left(\frac{\Delta E_{c1}(P)-\Delta E_{c2}(P)}{kT}\right)\right)}{2(1+2K)\left(1+2\exp\left(\frac{\Delta E_{c1}(P)-\Delta E_{c2}(P)}{kT}\right)\right)}-1\right], \quad (17)$$

where $K = \mu\| / \mu^{\perp} = 0{,}87$. $\mu\| / \mu^{\perp}$ – anisotropy mobility factor.

In the unstrained semiconductor hole mobility is [3]:

$$\mu_{p0} = \frac{q\tau}{m_e^{3/2}\left(m_л^{1/2}+m_m^{1/2}\right)}, \quad (18)$$

where q – electron charge; $m_л$ and m_m – effective masses of high mobility and heavy hole; τ – relaxation time, which is the same for both types of holes.

Hole mobility under pressure is evaluated as the following expression [6]:

$$\mu_p(P) = \frac{p_1\mu_1 + p_2\mu_2}{p_1 + p_2}, \quad (19)$$

де p_1 та p_2 – hole concentrations in the upper and bottom splitted zones; μ_1 та μ_2 – appropriate mobilities.

Deformation increment of the holes mobility is then equal to:

$$\Delta\mu_n(P) = \frac{q\tau}{m_e^{3/2}}\left[m_л^{\frac{1}{2}}\frac{\left(1+\left(\frac{m_m}{m_л}\right)^2\exp\left(\frac{\Delta E_{v-}(P)-\Delta E_{v+}(P)}{kT}\right)\right)}{\left(1+\left(\frac{m_m}{m_л}\right)^{\frac{3}{2}}\exp\left(\frac{\Delta E_{v-}(P)-\Delta E_{v+}(P)}{kT}\right)\right)}-\left(m_л^{\frac{1}{2}}+m_m^{\frac{1}{2}}\right)\right], \quad (20)$$

where $\Delta E_{v+}(P)$ – deformation increment of valence band apex when deformed; $\Delta E_{v-}(P)$ – deformation increment of valence band bottom part when deformed.

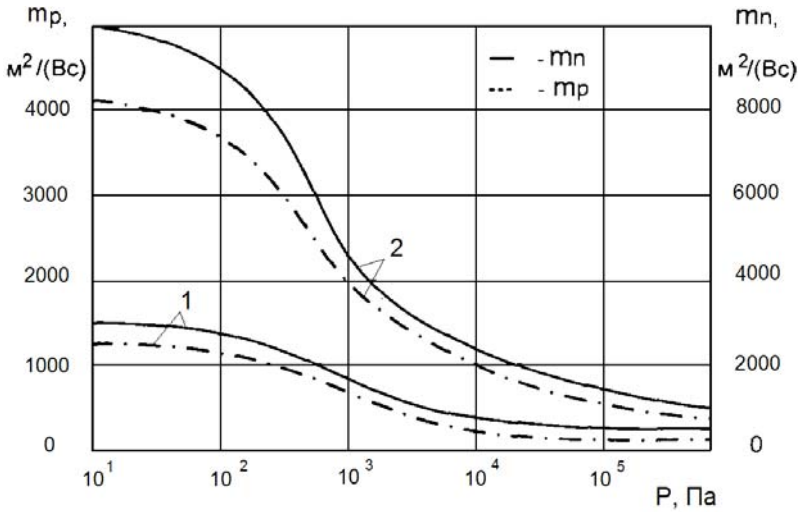

Fig. 3. Charge carriers dependency on pressure

As electric field E, current density j and mechanical stress ξ are directed along the crystallographic axis <100>, relation E/j is equal to[7]

$$E / j = \rho_0 + \Delta\rho = \rho_0(1+\tau_1\xi), \quad (21)$$

where ρ_0 – material specific resistance at $\xi = 0$; τ_1 – longitudinal piezoresistance coefficient, which depends on crystallographic direction in the semiconductor material:

$$\tau_1 = \tau_{11} + 2(\tau_{44} + \tau_{12} - \tau_{11}) \cdot (l^2 m^2 + l^2 n^2 + m^2 n^2), \quad (22)$$

where τ_{11}, τ_{12}, τ_{44} – cubic crystals piezoresistance coefficients; l, m, n – direction cosines of the angles between the direction of pressure P effect and crystallographic axes Ox_1, Ox_2, Ox_3 chosen correspondingly.

So, deformation increment of the specific resistance of the semiconductor material $\Delta\rho$ may be defined as [8]:

$$\Delta\rho(P) = \rho_1 \tau_1 \xi . \quad (23)$$

Conclusion

Deformation effects in the semiconductor structures under pressure have been studied. Theoretical dependencies of the described effect on electrophysical parameters of semiconductor structures, through the instrumentality of which semiconductor devices behavior under pressure may be simulated, have been defined.

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