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*Vasyl Stefanyk Precarpathian National University*

**ФІЗИКА І ХІМІЯ ТВЕРДОГО ТІЛА**
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S.V. Luniov[1], P.F. Nazarchuk[1], O.V. Burban[2]

# Electrical Properties of Strained Germanium Nanofilm

[1]*Lutsk National Technical University, Lutsk, Ukraine, luniovser@ukr.net*
[2]*Volyn Professional College of the National University of Food Technologies, Lutsk, Ukraine, sashaboorban@gmail.com*

Dependences of the concentration of intrinsic current carriers, electron and hole mobilities and specific conductivity for strained germanium nanofilms grown on the Si, $Ge_{(0.64)}Si_{(0.36)}$ and $Ge_{(0.9)}Si_{(0.1)}$ substrates with crystallographic orientation (001), on their thickness at different temperatures were calculated on the basis of the statistics of non-degenerate two-dimensional electron and hole gas in semiconductors. The electrical properties of such nanofilms are determined by the peculiarities of their band structure. It is established that the effects of dimensional quantization, the probability of which increases with decreasing temperature, become significant for germanium nanofilms with the thickness of $d < 7$ nm. The presence of such effects explains the significant increase in the specific conductivity and the decrease in the intrinsic concentration of current carriers for these nanofilms. The electron and hole mobility in the investigated germanium nanofilms is lower in relation to such unstrained nanofilms. Only for the strained germanium nanofilm with the thickness of $d > 50$ nm grown on the $Ge_{(0.9)}Si_{(0.1)}$ substrate, an increase in the hole mobility at room temperature of more than 1.5 times was obtained. The obtained results of the electrical properties of strained germanium nanofilms can be used in producing on their basis new elements of nanoelectronic.

**Keywords:** internal mechanical strains, strained germanium nanofilms, quantum-dimensional effects, intrinsic carrier concentration, specific conductivity, electron and hole mobility.

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## Introduction

Quantum effects that arise in nanostructures play an important role in the processes of current transfer and ultimately determine the electrical properties of nanomaterials. In recent years, many theoretical and experimental investigations were devoted to the study of various types of semiconductor heterosystems. This is due to the prospects of their application in nanoelectronics and laser technology [1]. As silicon technology remains the basis of modern micro- and nanoelectronics, the design of new semiconductor devices based on its heterostructures is very attractive and promising. Germanium is the only chemical element that produces heterostructures on silicon substrates in a wide range of component composition and layer thickness. The quality of the interface of the two materials is determined by the mismatch of their crystal lattices. In many cases, heterojunctions are formed from materials whose lattice constants differ substantially leading to significant mechanical strains [2, 3]. This yields very thin films on the surface of substrate that are used in optoelectronic devices, for instance, in the lasers based on quantum wells and electro-optical modulators [3-8]. Specifically, high hole mobility was found typical of strained germanium quantum wells in [9-11]. This enables the design of p-MOSFET and p-MODFET transistors with high-conductivity channels based on such quantum wells [10, 12]. The magnitude of the hole mobility in strained germanium quantum wells, like in bulk single crystals, is determined by the available scattering mechanisms of current carriers and deformation restructuring of the valence band of quantum well. The presence of internal mechanical strains leads to changes of the effective mass of the carriers, the relaxation time of different scattering mechanisms and, accordingly, the electron or hole mobility in quantum wells [13]. Theoretical models to calculate the carrier mobility in germanium quantum

wells were developed in [14, 15]. Good agreement of the experimental measurements of Hall mobility and the corresponding theoretical calculations at high temperatures was achieved by the authors of [15] on conditions of carrier scattering on ionized impurities and acoustic phonons. The slight difference of the experimental and theoretical results was explained by the disregard of the intervalley and electron-electron scattering mechanisms in the calculations. The design of various electronic devices using strained germanium quantum wells requires also, in addition to the magnitude of the mobility, the information on the carrier concentration and conductivity for such quantum wells.

Therefore, a comprehensive study of the effect of internal mechanical strains and quantum-size effects on the electrical properties of germanium quantum wells is requiredto develop recommendations of the synthesis and optimization of performance characteristics of modern nanoelectronics devices made with such nanostructures.

Such a study was performed in our previous work [16] for germanium nanofilms grown on silicon (001) substrate. Due to the presence of significant internal mechanical strains in the nanofilm, four $\Delta_1$ minima of Ge conduction band emerge as the lowest on the energy scale in its band structure, and the valence band of the heavy holes form the top. It was established that such a radical deformation restructuring of the band structure at room temperature leads to significant increase of the concentration of free carriers in the nanofilm and, as a consequence, specific conductivity. For germanium nanofilms of thickness d < 7 nm, the gigantic increase of the specific conductivity is explained by the significant increase of the role of quantum-dimensional effects.

In this paper, we consider the most general case of the effect of different structures of the conduction band and the valence band on the electrical properties of a strained germanium nanofilm at various temperatures. It was calculated in [17] for germanium nanofilm grown on a $Ge_{(x)}Si_{(1-x)}$ (001) substrate that the energy positions of $L_1$ and $\Delta_1$ minima will be the same for x = 0.64.The conduction band of the nanofilm will then be formed by both $L_1$ and $\Delta_1$ minima. For the cases of x = 0 and x = 0.9, the lowest minima on the energy scale are $\Delta_1$ and $L_1$, respectively. These minima will determine the electrical properties of germanium nanofilm. Also in the case of x = 0.9, the split of the bands of light and heavy holes is insignificant, and the calculations must take into account the contribution of both bands to the phenomena of carrier transport. Therefore, we calculated the concentration of intrinsic carriers, specific conductivity, electron and hole mobility at various temperatures for the strained germanium nanofilms grown on Si, $Ge_{(0.64)}Si_{(0.36)}$ and $Ge_{(0.9)}Si_{(0.1)}$ substrates with crystallographic orientation (001).

# I. Theory and computational details

For the case of non-degenerate gas of current carriers, the electron concentrations in $L_1$ and $\Delta_1$ minima of the conduction band, light and heavy holes of the valence band of the strained Ge nanofilm are expressed as [16, 17]:

$$n_{L_1} = \left( \frac{2}{d} \sum_{n=1}^{\infty} e^{-\frac{h^2 n^2}{8 m_{\parallel}^{L_1} kTd^2}} \right) \frac{2\pi m_{\perp}^{L_1} kT}{h^2} \cdot e^{-\frac{E_F - E_{L_1}}{kT}},$$

$$n_{\Delta_1} = \left( \frac{2}{d} \sum_{n=1}^{\infty} e^{-\frac{h^2 n^2}{8 m_{\parallel}^{\Delta_1} kTd^2}} \right) \frac{2\pi m_{\perp}^{\Delta_1} kT}{h^2} \cdot e^{-\frac{E_F - E_{\Delta_1}}{kT}}, \quad (1)$$

$$p_1 = \left( \frac{2}{d} \sum_{n=1}^{\infty} e^{-\frac{h^2 n^2}{8 m_1 kTd^2}} \right) \frac{2\pi m_1 kT}{h^2} \cdot e^{-\frac{E_F - E_{V_1}}{kT}},$$

$$p_2 = \left( \frac{2}{d} \sum_{n=1}^{\infty} e^{-\frac{h^2 n^2}{8 m_2 kTd^2}} \right) \frac{2\pi m_2 kT}{h^2} \cdot e^{-\frac{E_F - E_{V_2}}{kT}}. \quad (2)$$

Here $n_{L_1}$, $n_{\Delta_1}$ are electron concentrations in $L_1$and $\Delta_1$ minima; $p_1$ and $p_2$ are light and heavy hole concentration; $d$ is the quantum wellthickness; $m_{\perp}^{L_1} = 0.082m_0$, $m_{\parallel}^{L_1} = 1.58m_0$, $m_{\perp}^{\Delta_1} = 0.32m_0$, $m_{\parallel}^{\Delta_1} = 1.65m_0$, $m_1 = 0.044m_0$, $m_2 = 0.28m_0$ are effective masses of conductivity for $L_1$, $\Delta_1$ minima and light and heavy holes, respectively [17, 18]; $m_0$ is the mass of free electron; $E_{L_1}$, $E_{\Delta_1}$, $E_{V_1}$, $E_{V_2}$ are energy positions of $L_1$, $\Delta_1$ minima andbands of light and heavy holes.

Total concentrations of electrons and holes in the conduction band and valence band are:

$$n = n_{L_1} + n_{\Delta_1}, \quad p = p_1 + p_2. \quad (3)$$

Then the concentration of intrinsic carriers in the strained nanofilm is [18]:

$$n_i(\varepsilon) = \sqrt{np}. \quad (4)$$

For the case of unstrained nanofilm, the concentration of intrinsic carriers is:

$$n_i(0) = \frac{4\pi kT}{h^2 d} \left( m_{\perp}^{L_1} m_p \right)^{1/2} \left[ \sum_{n=1}^{\infty} e^{-\frac{h^2 n^2}{8 m_{\parallel}^{L_1} kTd^2}} \cdot \sum_{n=1}^{\infty} e^{-\frac{h^2 n^2}{8 m_p kTd^2}} \right]^{1/2} \cdot e^{-\frac{E_g(0)}{2kT}}, \quad (5)$$

Where $m_p$ = 0.193$m_0$ is the effective mass of conductivity for holes, $E_g(0)$ = 0.66 eV [18].

The specific conductivity for unstrained $\sigma(0)$ and strained $\sigma(\varepsilon)$ nanofilms can be represented as follows:

$$\begin{aligned}\sigma(0) &= qn_i(0)(\mu_{L_1} + \mu_p),\\ \sigma(\varepsilon) &= qn_i(\varepsilon)(\mu_n(\varepsilon) + \mu_p(\varepsilon)),\end{aligned} \tag{6}$$

where $\mu_{L_1}, \mu_p$ is themobility of electrons and holes in the unstrained nanofilm; $\mu_n(\varepsilon)$ and $\mu_p(\varepsilon)$ is the effective mobility of electrons and holes in the strained nanofilm. Effective carrier mobility can be found from the ratios^

$$\begin{aligned}\mu_n(\varepsilon) &= \frac{\mu_{L_1} n_{L_1} + \mu_{\Delta_1} n_{\Delta_1}}{n_{L_1} + n_{\Delta_1}},\\ \mu_p(\varepsilon) &= \frac{\mu_1 p_1 + \mu_2 p_2}{p_1 + p_2},\end{aligned} \tag{7}$$

where $\mu_1$ and$\mu_2$ is the mobility of light and heavy holes, respectively. Taking into account Eqs. (1) and (2):

$$\begin{aligned}\frac{n_{L_1}}{n_{\Delta_1}} &= \frac{\sum_{n=1}^{\infty} e^{-\frac{h^2 n^2}{8 m_{\parallel}^{L_1} kTd^2}}}{\sum_{n=1}^{\infty} e^{-\frac{h^2 n^2}{8 m_{\parallel}^{\Delta_1} kTd^2}}} \left(\frac{m_{\perp}^{L_1}}{m_{\perp}^{\Delta_1}}\right) e^{\frac{E_{\Delta_1} - E_{L_1}}{kT}} = A,\\ \frac{p_1}{p_2} &= \frac{\sum_{n=1}^{\infty} e^{-\frac{h^2 n^2}{8 m_1 kTd^2}}}{\sum_{n=1}^{\infty} e^{-\frac{h^2 n^2}{8 m_2 kTd^2}}} \left(\frac{m_1}{m_2}\right) e^{\frac{E_{V_1} - E_{V_2}}{kT}} = B.\end{aligned} \tag{8}$$

Then Eq. (7) can be written as:

$$\begin{aligned}\mu_n(\varepsilon) &= \frac{\mu_{L_1} A + \mu_{\Delta_1}}{1 + A},\\ \mu_p(\varepsilon) &= \frac{\mu_1 B + \mu_2}{1 + B}.\end{aligned} \tag{9}$$

The relative changes in the mobility of electrons and holes in the strained germanium nanofilm can be represented as:

$$\frac{\mu_n(\varepsilon)}{\mu_n(0)} = \frac{A + b_1}{1 + A}, \quad \frac{\mu_p(\varepsilon)}{\mu_p(0)} = \frac{b_2 B + b_3}{1 + B}, \tag{10}$$

where $b_1 = \frac{\mu_{\Delta_1}}{\mu_{L_1}}$, $b_2 = \frac{\mu_1}{\mu_p(0)}$, $b_3 = \frac{\mu_2}{\mu_p(0)}$.

The value $b_1 = 0.088$ was calculated in [19] for the case of electron scattering on acoustic phonons. The values of constants $b_2$ and $b_3$ can be similarly calculated. The expressions for the mobility of holes can be written as:

$$\begin{aligned}\mu_p(0) &= \frac{q}{m_p} < \tau_p >,\\ \mu_1 &= \frac{q}{m_1} < \tau_1 >,\\ \mu_2 &= \frac{q}{m_2} < \tau_2 >,\end{aligned} \tag{11}$$

where $< f(x) >= \frac{4}{3\sqrt{\pi}} \int_0^{\infty} dx x^{3/2} e^{-x} f(x)$.

Relaxation times of holes for scattering on acoustic phonons are [20]:

$$\begin{aligned}\tau_p &= \frac{\pi \hbar^4 C_e}{m_V^{3/2} \Xi_{ac}^2 \sqrt{2} (kT)^{3/2} \sqrt{x}},\\ \tau_1 &= \frac{\pi \hbar^4 C_e}{m_1^{3/2} \Xi_{ac}^2 \sqrt{2} (kT)^{3/2} \sqrt{x}},\\ \tau_2 &= \frac{\pi \hbar^4 C_e}{m_2^{3/2} \Xi_{ac}^2 \sqrt{2} (kT)^{3/2} \sqrt{x}},\end{aligned} \tag{12}$$

where $m_V = 0.292 m_0$, $\Xi_{ac} = 8.7$ eV, $C_e = 1.903 \cdot 10^{11}$ Pa [18, 20].

Taking into account Eqs. (10-12), the relative change of the mobility of holes in the strained Ge nanofilm is:

$$\frac{\mu_p(\varepsilon)}{\mu_p(0)} = \frac{m_V^{3/2} m_p (m_2^{5/2} B + m_1^{5/2})}{(1 + B)(m_1 m_2)^{5/2}}. \tag{13}$$

It was shown in [19] that the mobility of electrons in the $L_1$ minimum of the conduction band can be presented as:

$$\mu_{L_1} = \frac{1}{3} \mu_{\parallel}^{L_1} + \frac{2}{3} \mu_{\perp}^{L_1}, \tag{14}$$

The components of the mobility tensor $\mu_{\parallel}^{L_1}$ and $\mu_{\perp}^{L_1}$ can be expressed in terms of the components of the relaxation time and the effective mass tensor:

$$\mu_{\parallel}^{L_1} = \frac{q}{m_{\parallel}^{L_1}} < \tau_{\parallel}^{L_1} >, \ \mu_{\perp}^{L_1} = \frac{q}{m_{\perp}^{L_1}} < \tau_{\perp}^{L_1} >. \tag{15}$$

The expressions for $\tau_{\parallel}^{L_1}$ and $\tau_{\perp}^{L_1}$ for electron scattering on acoustic phonons are equal to [19]:

$$\tau_{\parallel}^{L_1} = \frac{a_{\parallel}^{L_1}}{\sqrt{k} T^{\frac{3}{2}}} \cdot \frac{1}{\sqrt{x}}, \ \tau_{\perp}^{L_1} = \frac{a_{\perp}^{L_1}}{\sqrt{k} T^{\frac{3}{2}}} \cdot \frac{1}{\sqrt{x}}. \tag{16}$$

(The necessary notations for $a_{\parallel}^{L_1}$ and $a_{\perp}^{L_1}$ in Eq. (16) are presented in the appendix of [19]).

Then, according to (14-16):

$$\mu_{L_1} = \frac{4q}{9\sqrt{\pi k T}^{\frac{3}{2}}}\left(\frac{a_{\parallel}^{L_1}}{m_{\parallel}^{L_1}} + 2\frac{a_{\perp}^{L_1}}{m_{\perp}^{L_1}}\right). \qquad (17)$$

The relative change of the specific conductivity of the strained germanium nanofilm, according to (6) is:

$$\frac{\sigma(\varepsilon)}{\sigma(0)} = \frac{n_i(\varepsilon)}{n_i(0)}\frac{b_4(1+B)+b_5B+b_6}{(1+B)(1+b_7)}, \qquad (18)$$

where $b_4 = \frac{\mu_n(\varepsilon)}{\mu_{L_1}} = \frac{A+b_1}{1+A}$,

$$b_5 = \frac{\mu_1}{\mu_{L_1}} = \frac{\pi\hbar^4 C_e}{\sqrt{2}km_1^{5/2}\Xi_{ac}^2\left(\frac{a_{\parallel}^{L_1}}{m_{\parallel}^{L_1}} + 2\frac{a_{\perp}^{L_1}}{m_{\perp}^{L_1}}\right)},$$

$$b_6 = \frac{\mu_2}{\mu_{L_1}} = \frac{\pi\hbar^4 C_e}{\sqrt{2}km_2^{5/2}\Xi_{ac}^2\left(\frac{a_{\parallel}^{L_1}}{m_{\parallel}^{L_1}} + 2\frac{a_{\perp}^{L_1}}{m_{\perp}^{L_1}}\right)},$$

$$b_7 = \frac{\mu_p}{\mu_{L_1}} = \frac{\pi\hbar^4 C_e}{\sqrt{2}km_V^{3/2}m_p\Xi_{ac}^2\left(\frac{a_{\parallel}^{L_1}}{m_{\parallel}^{L_1}} + 2\frac{a_{\perp}^{L_1}}{m_{\perp}^{L_1}}\right)}.$$

Obtained expressions were used to calculated the dependences of the intrinsic carrier concentration, electron and hole mobility, and specific electrical conductivity for strained germanium nanofilms on their thickness at various temperatures. Computer algebra software system MathCad 14, in particular the built-in formula editor, was used in the calculations. The software enablesautomatic calculations using appropriate numerical methods and algorithms [17].

## II. Results and discussion

Dependences of the concentration of intrinsic carriers for Ge nanofilms grown on Si, $Ge_{(0.64)}Si_{(0.36)}$ and $Ge_{(0.9)}Si_{(0.1)}$(001) substrates on their thickness at various temperatures are presented in Figs. 1-3.

The concentration of intrinsic carriers at T = 200 K is less than $10^{10}$ $cm^{-3}$ for unstrained Ge and $Ge/Ge_{(0.9)}Si_{(0.1)}$ nanofilms of arbitrary thickness. That is, such nanofilms will be dielectrics in terms of their electrical conductivity, especially when their thickness is d < 7 nm. The increase in the intrinsic carrier concentration for the strained Ge nanofilms with the thickness d > 7 nm *vs* unstrained ones is explained, first of all, by the decrease of the band gap due to internal mechanical strains [19]. The maximum relative increase of the concentration of intrinsic current carriers is observed for the Ge/Si nanofilm because in this case the magnitude of internal mechanical strains is the largest, and the band gap of such nanofilm will be the smallest compared to $Ge/Ge_{(0.9)}Si_{(0.1)}$ and $Ge/Ge_{(0.64)}Si_{(0.36)}$ nanofilms. A significant decrease in the intrinsic carrierconcentration

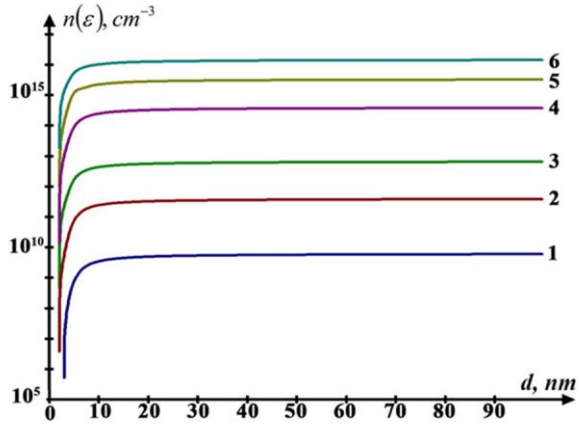


**Fig. 1.** Dependences of intrinsic carriers concentration for the Ge/Si nanofilm on its thickness at different temperatures: 4 – 200 K, 5 – 250 K, 6 – 300 K. Curves 1, 2 and 3 are theoretical calculations for the unstrained Ge nanofilm at 200 K, 250 K and 300 K respectively.

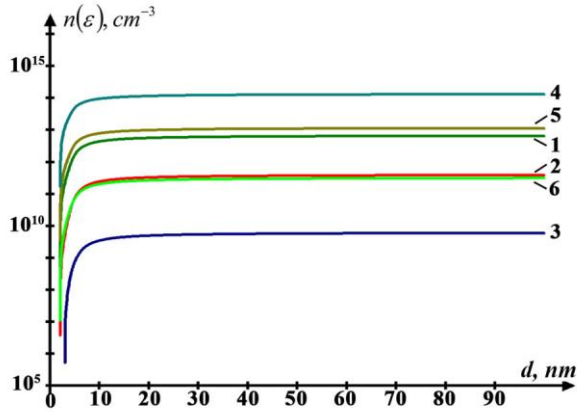


**Fig. 2.** Dependences of concentration of intrinsic carriers for the $Ge/Ge_{(0,64)}Si_{(0,36)}$ nanofilm on its thickness at different temperatures: 4 – 200 K, 5 – 250 K, 6 – 300 K. Curves 1, 2 and 3 same as Fig. 1.

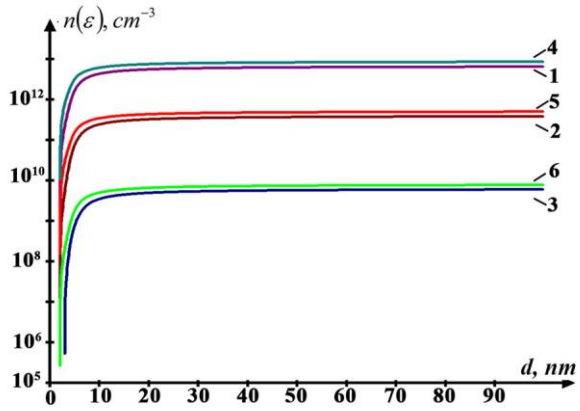


**Fig. 3.** Dependences of concentration of intrinsic carriers for the $Ge/Ge_{(0.9)}Si_{(0.1)}$ nanofilm on its thickness at different temperatures: 4 – 200 K, 5 – 250 K, 6 – 300 K. Curves 1, 2 and 3 same as Fig. 1.

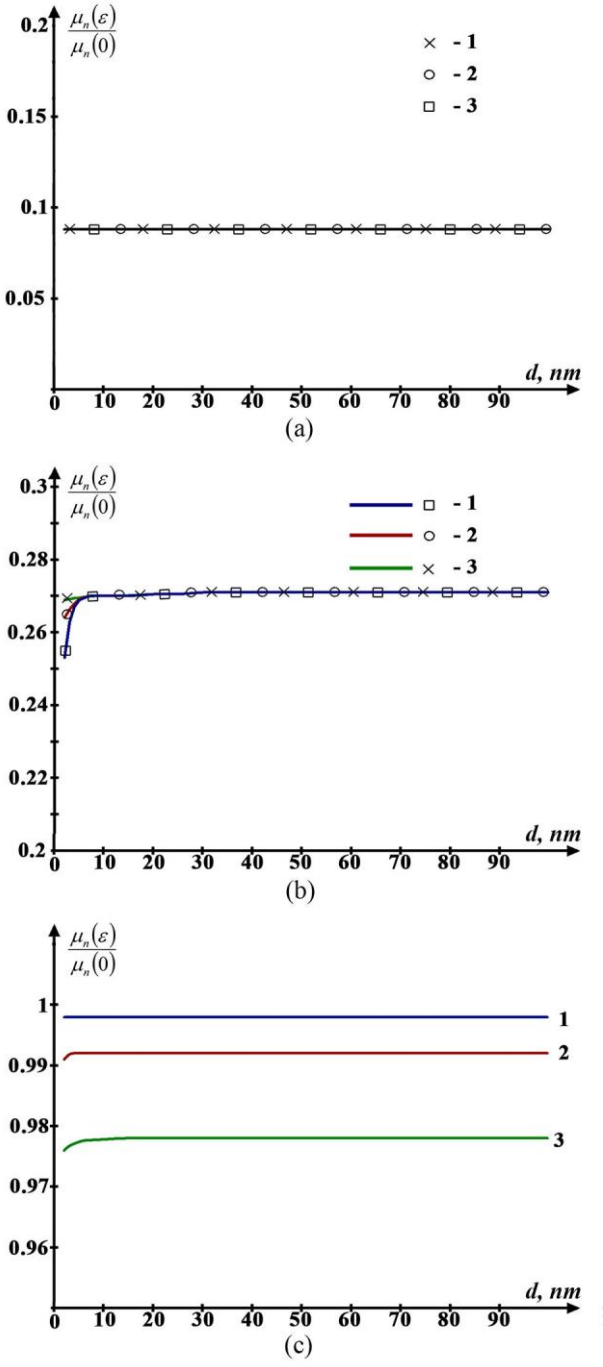


**Fig. 4.** Dependence of electron mobility for the Ge/Si (a), $Ge/Ge_{(0.64)}Si_{(0.36)}$ (b) and $Ge/Ge_{(0.9)}Si_{(0.1)}$ (c) nanofilms on the film thickness at different temperatures: 1 – 200 K, 2 – 250 K, 3 – 300 K.

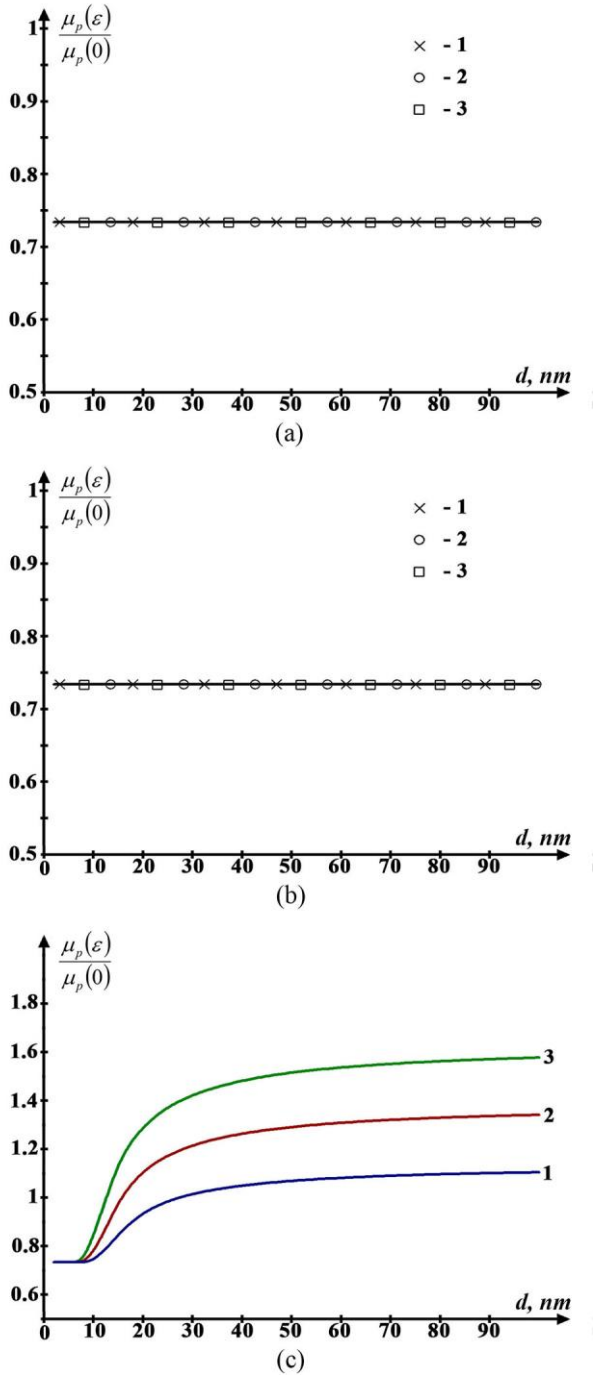


**Fig. 5.** Dependence of hole mobility for the Ge/Si (a), $Ge/Ge_{(0.64)}Si_{(0.36)}$ (b) and $Ge/Ge_{(0.9)}Si_{(0.1)}$ (c) nanofilms on the film thickness at different temperatures: 1 – 200 K, 2 – 250 K, 3 – 300 K.

for germanium nanofilms of $d < 7$ nm thickness is relatedto the increase in the effect of dimensional quantization [16]. An additional factor that increases the effect of dimensional quantization for such nanofilms is the temperature decrease.This leads to a sharper decrease in the concentration of carriers upon the reduction of the nanofilm thickness.

Dependences of electron and hole mobility for Ge nanofilms grown on Si, $Ge_{(0.64)}Si_{(0.36)}$ and $Ge_{(0.9)}Si_{(0.1)}$ substrates are presented in Figs. 4, 5. The electron mobility decreases with increasing silicon content in the substrate, and hence the magnitude of internal mechanical strains in such nanofilms [19], and is virtually independent of the thickness as well as temperature.

The hole mobility for the Ge/Si and $Ge/Ge_{(0.64)}Si_{(0.36)}$ nanofilms (Fig. 5a, 5b) decreases relative to the unstrained nanofilm by approximately 27 percent. This decrease in mobility does not depend on the film thickness, temperature, and also, unlike electron mobility (Fig. 4a, 4b, and 4c), on the magnitude of internal mechanical strains. Only for the $Ge/Ge_{(0.9)}Si_{(0.1)}$ nanofilm the hole mobility will depend on both the film thickness and the temperature (Fig. 5c). The increase of the role of

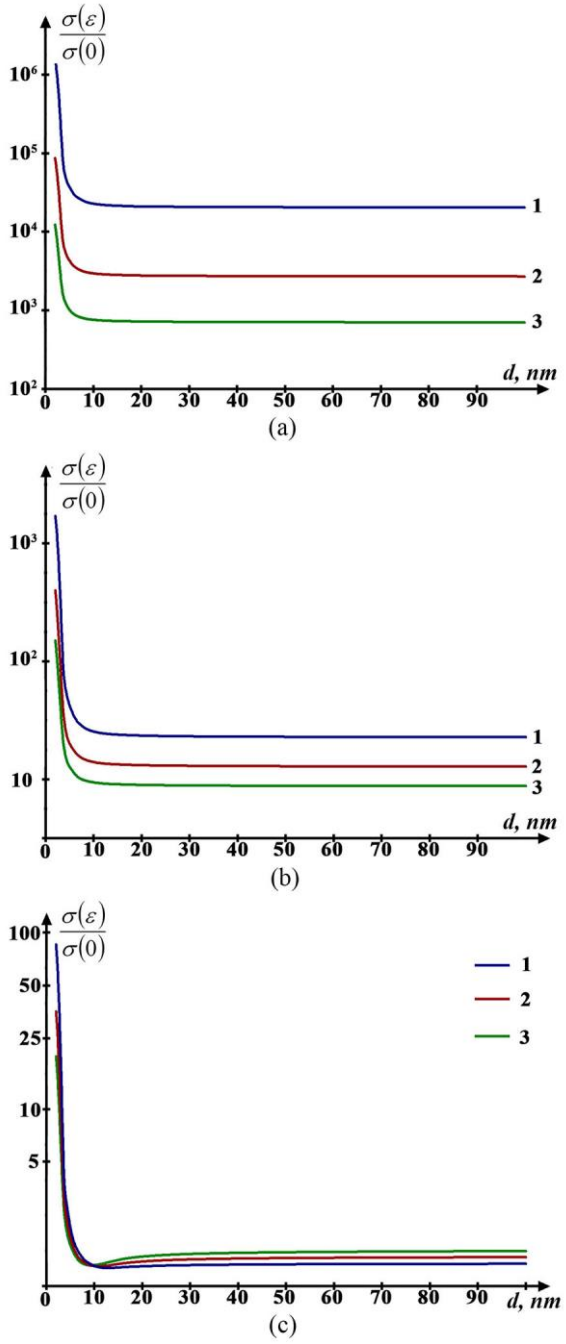


**Fig. 6**. Dependences of the specific electrical conductivity of the Ge/Si (a), Ge/$Ge_{(0.64)}Si_{(0.36)}$ (b) and Ge/$Ge_{(0.9)}Si_{(0.1)}$ (c) nanofilms on the film thickness at different temperatures: 1 – 200 K, 2 – 250 K, 3 – 300 K.

an effect of dimensional quantization with decreasing nanofilm thickness and temperature leads to a reduction in the hole mobility in this case. The increase of the hole mobility is achieved for nanofilms of $d > 15$ nm thickness at 250 K and 300 K (Fig. 5c, curves 2 and 3) and for $d > 25$ nm thickness at 200 K (Fig. 5c, curve 1). The hole mobility due to the presence of internal mechanical strains increases at room temperature by more than 1.5 times for nanofilms of $d > 50$ nm thickness. As shown in [17, 19], the valence band of heavy holes tops the energy spectrum of the strained Ge/$Ge_{(0.9)}Si_{(0.1)}$ nanofilm. Redistribution of holes with various effective mass between the bands of light and heavy holes due to temperature variation leads to changes in the effective mobilityof holes. The concentration of light holes increases with temperature, consequently, the effective mass of holes decreases and their mobility increases. Therefore, the decrease in the probability of quantum-dimensional effects and the effective mass of holes upon increasing temperature explains the peculiarities of the obtained dependences of hole mobility for Ge nanofilm on the $Ge_{(0.9)}Si_{(0.1)}$ substrate.

Dependences of the specific conductivity for Ge/Si, Ge/$Ge_{(0.64)}Si_{(0.36)}$ and Ge/$Ge_{(0.9)}Si_{(0.1)}$ nanofilms on the film thickness at various temperatures are presented in Fig. 6.

The relative increase of the specific conductivity of Ge/Si and Ge/$Ge_{(0,64)}Si_{(0,36)}$ nanofilms of $d > 7$ nm thickness (Fig. 6a and 6b) is explained by the increased concentration of intrinsic carriers due to smaller band gap resulting from the effect of internal mechanical strains.

The significant increase in the specific conductivity of such nanofilms of $d < 7$ nm thickness, especially at decreased temperatures, is explained (as in the case of similar dependences of intrinsic carrier concentration) by the substantially increasing role of the quantum effects. The increase of the Ge/$Ge_{(0.9)}Si_{(0.1)}$ nanofilm thickness leads to a slight increase of its specific conductivity witha minimum at $d \approx 10$ nm which is associated with the increase of the effective mobility of holes.

## Conclusions

The electrical properties of Ge/Si, Ge/$Ge_{(0.64)}Si_{(0.36)}$ and Ge/$Ge_{(0.9)}Si_{(0.1)}$ nanofilms are determined primarily by the features of their band structure which depends on the magnitude of the internal mechanical strains that exist in such nanofilms and temperature. The increase of the specific conductivity and intrinsic carrier concentration relative to unstrained Ge nanofilms is explained by the decrease of Ge band gap under internal distortion fields. It is established that the specific conductivity and intrinsic carrier concentration particularly increase in nanofilms of $d < 7$ nm thickness. In this case, in addition to the mechanism of intrinsic conductivity, the influence of dimensional quantization becomes significant, the efficiency of which increases with decreasing temperature. The electron mobility for the investigated nanofilms is lower than that of unstrained nanofilms. Here, quantum-dimensional effects and temperature variation have virtually no effect on the relative decrease of mobility. Both hole and electron mobility in the Ge/Si and Ge/$Ge_{(0.64)}Si_{(0.36)}$ nanofilms decreases due to internal mechanical strains. Such a decrease in mobility for these nanofilms does not depend on the magnitude of internal mechanical strains and will be the same. An increase of hole mobility of more than 50 per cent is observed for the strained Ge/$Ge_{(0.9)}Si_{(0.1)}$ nanofilm at room temperature when the nanofilm thickness is $d > 50$ nm. The reason for such mobility increase is the decrease of the effective mass of holes due to the deformation restructuring of Ge valence band and

the weakening of the role of quantum-dimensional effects.

The presented calculations of the electrical properties of strained germanium nanofilms can be used in the development of the scientific basis of the synthesis of such nanofilms and the creation of new elements and devices of nanoelectronics. In particular, observed increase of hole mobility for the strained $Ge/Ge_{(0.9)}Si_{(0.1)}$ nanofilm can be used in the design of high-conductivity channels of p-MOSFET and p-MODFET transistors using such nanofilms.

***Luniov S.*** - Ph.D. in Physics and Mathematical Sciences, associate professor of Department of Physics and Higher Mathematics;
***Nazarchuk P.*** - Ph.D. in Physics and Mathematical Sciences, associate professor of Department of Physics and Higher Mathematics
***Burban O.*** - Ph.D. in Physics and Mathematical Sciences, teacher of Department Computer Science and Computer Engineering.

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С.В. Луньов[1], П.Ф. Назарчук[1], О.В. Бурбан[2]

# Електричні властивості напруженої наноплівки германію

[1]*Луцький національний технічний університет, Луцьк, Україна, luniovser@ukr.net*
[2]*Волинський фаховий коледж Національного університету харчових технологій, Луцьк, Україна, sashaboorban@gmail.com*

На основі статистики невиродженого двовимірного електронного та діркового газу в напівпровідниках проведено розрахунки залежностей концентрації власних носіїв струму, рухливостей електронів та дірок та питомої електропровідності для напружених наноплівок германію, вирощених на підкладках Si, $Ge_{(0,64)}Si_{(0,36)}$ та $Ge_{(0,9)}Si_{(0,1)}$ з кристалографічною орієнтацією (001), від їх товщини при різних температурах. Електричні властивості таких наноплівок визначаються особливостями їх зонної структури. Встановлено, що для наноплівок германію, товщиною $d < 7$ нм, суттєвими стають ефекти розмірного квантування. Наявність таких ефектів пояснює значне зростання питомої електропровідності та зменшення власної концентрації носіїв струму для таких наноплівок. Рухливість електронів та дірок в досліджуваних наноплівках германію є меншою по відношенню до таких ненапружених наноплівок. Лише для напруженої наноплівки германію, товщиною $d > 50$ нм, вирощеній на підкладці $Ge_{(0,9)}Si_{(0,1)}$, було одержано зростання рухливості дірок більше, ніж в 1,5 рази. Одержані результати електричних властивостей напружених наноплівок германію можуть бути використанні для одержання на їх основі нових елементів наноелектроніки.

**Ключові слова:** внутрішні механічні напруження, напружені наноплівки германію, квантово-розмірні ефекти, концентрація власних носіїв струму, питома провідність, рухливість електронів та дірок.