Vol 16 No 12, December 2007
1009-1963/2007/16(12)/3827-05

Chinese Physics

© 2007 Chin. Phys. Soc.
and IOP Publishing Ltd

Determination of conduction band edge characteristics of strained $Si/Si_{1-x}Ge_x$*

Song Jian-Jun(宋建军), Zhang He-Ming(张鹤鸣), Hu Hui-Yong(胡辉勇), Dai Xian-Ying(戴显英), and Xuan Rong-Xi(宣荣喜)

Key Laboratory of Ministry of Education for Wide Band-Gap Semiconductor Materials and Devices, School of Microelectronics, Xidian University, Xi'an 710071, *China*

(Received 24 April 2007; revised manuscript received 16 May 2007)

The feature of conduction band (CB) of Tensile-Strained Si(TS-Si) on a relaxed $Si_{1-x}Ge_x$ substrate is systematically investigated, including the number of equivalent CB edge energy extrema, CB energy minima, the position of the extremal point, and effective mass. Based on an analysis of symmetry under strain, the number of equivalent CB edge energy extrema is presented; Using the K·P method with the help of perturbation theory, dispersion relation near minima of CB bottom energy, derived from the linear deformation potential theory, is determined, from which the parameters, namely, the position of the extremal point, and the longitudinal and transverse masses (m_l^* and m_t^*) are obtained.

Keywords: strained $Si/Si_{1-x}Ge_x$, conduction-band, K·P method
PACC: 7360F, 7125C, 7115T

1. Introduction

The continual scaling of device dimensions is reaching the physical limits of the conventional silicon technology. To extend the lifetime of silicon, other novel structures and compatible materials have been studied. One of the most promising new material systems is strained silicon on a relaxed $Si_{1-x}Ge_x$ substrate, which delivers significant enhancements in device performance with relatively small changes in the overall device design and technology.[1,2]

Effective device design is ultimately based on an understanding of correct material parameters and accurate simulation of carrier transport in the device. However, To date there have been few reported results for the $Si/Si_{1-x}Ge_x$ CB edge compared with the wide reporting of the theoretical and experimental studies of valence band edge.[3−6]

The main goal of this paper is to provide CB edge parameters under strain arising from growth on various oriented substrates such as the number of equivalent CB edge energy extrema, CB energy minima, the position of the extremal point, longitudinal and transverse masses m_l^* and m_t^* that are needed for quantitative transport calculations. The work is performed in the framework of the K·P method. The number of equivalent CB edge energy extrema is obtained by an analysis of symmetry, and then dispersion relation near minima of CB bottom energy, derived from the linear deformation potential theory, is determined using the K·P method with the help of perturbation theory, from which the parameters, namely, the position of the extremal point, m_l^* and m_t^* are obtained, which are in good accordance with the ones cited from Refs.[7,8].

2. Analysis of symmetry under strain

In the CB of Si there are six distinct symmetrically arranged minima along the (100) directions. The biaxial tensile stress in a Si epitaxial layer grown on various oriented $Si_{1-x}Ge_x$ substrates by ultrahigh vacuum chemical vapour deposition (UHV-CVD) induces a deformation that causes the change of Δ_1 valleys. Partial symmetry is retained in the lattice of the strained film. Under a tetragonal distortion, arising from the growth on a (001) substrate, the six Δ_1 valleys are not symmetrically equivalent, with the [±100] and [0±10] valleys shifting together and splitting from the [00±1] valleys which constitutes the CB edge as shown in Fig.1. For rhombohedral distortion arising from the growth on a (111) substrate, all Δ_1

*Project supported by the National Defence Pre-research Foundation of China (Grant Nos 51308040203 and 51408061105DZ0171).

valleys are symmetrically equivalent and shift together as shown in Fig.2. The number of equivalent CB edge energy extrema is unchanged. The growth on a substrate of the third orientation, (101) considered in this work, produces a monoclinic distortion and splits the Δ_1 levels. Figure 3 shows that the [±100] and [00±1] valleys are symmetrically equivalent, splitting from the [0±10] valley, i.e. the number of equivalent CB edge energy extrema is four.

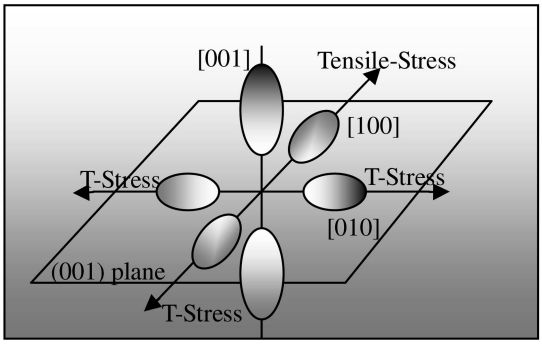


Fig.1. Schematic equi-energy surfaces of the six split valleys in the first CB in Si/(001)$Si_{1-x}Ge_x$.

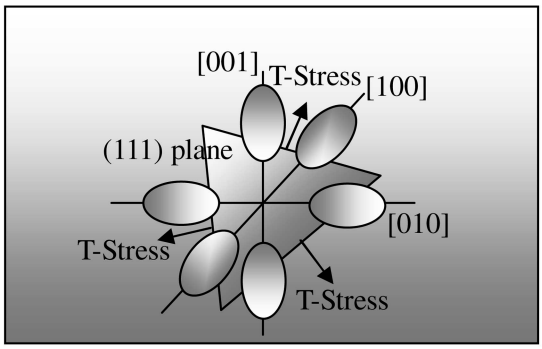


Fig.2. The same legend as that in Fig.1, but for Si/(111)$Si_{1-x}Ge_x$.

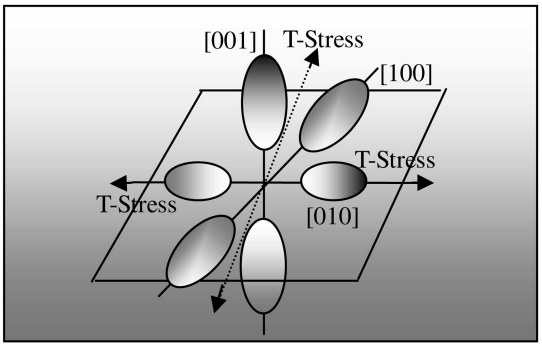


Fig.3. The same legend as that in Fig.1, but for Si/(101)$Si_{1-x}Ge_x$.

3. K·P theoretical[9] derivation

In this section, CB edge parameters in a strained layer, such as the position of extremal point, m_l^* and m_t^*, will be discussed using the K·P method with the help of perturbation theory.

In the single electron approximation, the eigenfunctions of the Schrödinger equation are the Bloch function

$$\Psi_{n\boldsymbol{k}}(\boldsymbol{r}) = \mathrm{e}^{\mathrm{i}\boldsymbol{k}\cdot\boldsymbol{r}} u_{n\boldsymbol{k}}(\boldsymbol{r}), \tag{1}$$

where n is the index of energy band, and the wave vector changes within the first Brillouin zone.

$$\left\{-\frac{\hbar^2}{2m_0}\nabla^2 + U'(\boldsymbol{r})\right\}\Psi(\boldsymbol{r}) = \varepsilon\,\Psi(\boldsymbol{r}), \tag{2}$$

$$U'(\boldsymbol{r}) = U_{\mathrm{unstrain}}(\boldsymbol{r}) + U_{\mathrm{Deformation}}(\boldsymbol{r}), \tag{3}$$

where, $U_{\mathrm{unstrain}}(\boldsymbol{r})$ is the periodic field of unstrained crystal lattice while an additional field $U_{\mathrm{Deformation}}(\boldsymbol{r})$ is induced by lattice deformation.

Under the biaxial stress imposed by the substrate, in the plane of the interface between the film and its substrate the film is forced to follow the lattice structure of its host substrate, and therefore lattice periodicity is preserved under such a strain. Moreover, the elastic strain is small enough to be treated as a small perturbation. Substituting function (1) into Eq.(2), yields Eq.(4) for a modulating functions $u_{n\boldsymbol{k}(\boldsymbol{r})}$, which has the periodicity of the unstrained crystal lattice.

$$\begin{aligned}&\left\{\frac{\hat{\boldsymbol{p}}^2}{2m_0} + \frac{\hbar}{m_0}\boldsymbol{k}\cdot\hat{\boldsymbol{p}} + \frac{\hbar^2k^2}{2m_0} + U'(\boldsymbol{r})\right\}u_{n\boldsymbol{k}}(\boldsymbol{r})\\ &= H_{\boldsymbol{k}}u_{n\boldsymbol{k}}(\boldsymbol{r}) = \varepsilon_n(\boldsymbol{k})u_{n\boldsymbol{k}}(\boldsymbol{r}),\end{aligned} \tag{4}$$

where $\hat{\boldsymbol{p}} = -\mathrm{i}\hbar\nabla$ is the momentum operator of the electron.

There are six equivalent energy extremal point $\boldsymbol{k}_0^s\,(s = 1,2,3,4,5,6)$ for bulk, unstrained Si, in the vicinity of which the band is non-degenerate. The strain resulting from the growth on a (001) substrate, (101) oriented substrate will lift partially the degeneracy of K wavevector starts, while there appears no reduction for the (111) case. As indicated in Section 2, the number of equivalent CB edge energy extrema is two, four and six, respectively.

We take an arbitrary extremal point $\boldsymbol{k}_0^i (i = 1{-}12)$ into account. Since for any given $\boldsymbol{k}$ the set $u_{n\boldsymbol{k}}$ forms a complete set in the space of functions having the periodicity of the lattice, we can expand $u_{n\boldsymbol{k}}$ for any $\boldsymbol{k}$ into functions for $\boldsymbol{k} = \boldsymbol{k}_0^i$. So we have

$$u_{n\boldsymbol{k}}(\boldsymbol{r}) = \sum A_{nn'}(\boldsymbol{k} - \boldsymbol{k}_0^i)u_{n\boldsymbol{k}_0^i}(\boldsymbol{r}). \tag{5}$$

This is called the $\boldsymbol{k}_0^i$-representation. By isolating the part $H_{\boldsymbol{k}_0^i}$ from Hamiltonian $H_{\boldsymbol{k}}$, Eq.(4) may be represented in the form

$$(H_{\boldsymbol{k}_0^i} + H_{\boldsymbol{k}\cdot\hat{\boldsymbol{p}}} + H_{\text{strain}})u_{n\boldsymbol{k}}(\boldsymbol{r}) = \varepsilon_n^i(\boldsymbol{k})u_{n\boldsymbol{k}}(\boldsymbol{r}), \quad (6)$$

where

$$H_{\boldsymbol{k}_0^i} = \frac{\hat{\boldsymbol{p}}^2}{2m_0} + \frac{\hbar}{m_0}\boldsymbol{k}_0^i\cdot\hat{\boldsymbol{p}} + \frac{\hbar^2 k_0^{i2}}{2m_0} + U_{\text{unstrain}}(\boldsymbol{r}), \quad (7)$$

$$H_{\boldsymbol{k}\cdot\hat{\boldsymbol{p}}} = \frac{\hbar}{m_0}\left[(\boldsymbol{k}-\boldsymbol{k}_0^i)\right]\cdot\hat{\boldsymbol{p}} + \frac{\hbar^2(k^2-k_0^{i2})}{2m_0}, \quad (8)$$

$$H_{\text{strain}} = U_{\text{Deformation}}(\boldsymbol{r}). \quad (9)$$

If $\boldsymbol{k}-\boldsymbol{k}_0^i$ is a sufficiently small quantity, the operator $H_{\boldsymbol{k}\cdot\hat{\boldsymbol{p}}}(\boldsymbol{k}-\boldsymbol{k}_0)+H_{\text{strain}}(\boldsymbol{k}-\boldsymbol{k}_0)$ may be considered as a small perturbation compared with the operator $H_{\boldsymbol{k}_0^i}$. Particularly, varying $\boldsymbol{k}$ in the vicinity of $\boldsymbol{k}_0^i$, the deformation potential field is taken as a constant, independent of the wavevector. It is convenient to denote $H_{\text{strain}}(\boldsymbol{k}-\boldsymbol{k}_0)$ as $U_{\boldsymbol{k}_0^i}$ for discussion.

Substituting the expansion expression (5) into Eq.(6), multiplying both sides of Eq.(6) by $u^*_{n\boldsymbol{k}_0^i}$ and integrating over the unit cell, we obtain a system of equations which give the eigenvalues as follows:

$$\sum_{n'}\Big\{\Big[\varepsilon_n^i(\boldsymbol{k}_0^i) + \frac{\hbar^2(k^2-k_0^{i2})}{2m_0} + U_{\boldsymbol{k}_0^i}\Big]\delta_{nn'}A_{nn'} + \frac{\hbar}{m_0}(\boldsymbol{k}-\boldsymbol{k}_0^i)\cdot\boldsymbol{p}_{nn'}(\boldsymbol{k}_0^i)\Big\}A_{nn'} = \varepsilon_n^i(\boldsymbol{k})A_{nn'}, \quad (10)$$

where

$$\boldsymbol{p}_{nn'}(\boldsymbol{k}_0^i) = \langle u_{n\boldsymbol{k}_0^i}|\hat{\boldsymbol{p}}|u_{n'\boldsymbol{k}_0^i}\rangle = \int_{\Omega_0} u^*_{n\boldsymbol{k}_0^i}\hat{\boldsymbol{p}}u_{n'\boldsymbol{k}_0^i}\mathrm{d}\boldsymbol{r} \quad (11)$$

is the matrix element of the momentum operator at point $\boldsymbol{k}=\boldsymbol{k}_0^i$. In deriving Eq.(10), the functions u are considered to be orthonormalized in the unit cell, i.e.

$$\int_{\Omega_0} u^*_{n\boldsymbol{k}_0^i}u_{n'\boldsymbol{k}_0^i}\mathrm{d}\boldsymbol{r} = \delta_{nn'}. \quad (12)$$

The corresponding terms of $H_{\boldsymbol{k}\cdot\hat{\boldsymbol{p}}} + H_{\text{strain}}$ in Eq.(10) may be visualized as small corrections to the energy $\varepsilon_n^i(\boldsymbol{k}_0^i)$. The dependence of energy on the wave vector may be obtained from Eq.(10) by using the ordinary perturbation theory as follows:

$$\varepsilon_n^i(\boldsymbol{k}) = \varepsilon_n^i(\boldsymbol{k}_0^i) + \varepsilon_n^{i'}(\boldsymbol{k}_0^i), \quad (13)$$

$$\varepsilon_n^{i'}(\boldsymbol{k}_0^i) = U_{\boldsymbol{k}_0^i} + \frac{\hbar^2(k^2-k_0^{i2})}{2m_0} + \frac{\hbar}{m_0}(\boldsymbol{k}-\boldsymbol{k}_0^i)\cdot\boldsymbol{p}_{nn'}(\boldsymbol{k}_0^i). \quad (14)$$

To the second order we obtain

$$\varepsilon_n^i(\boldsymbol{k}) = \varepsilon_n^i(\boldsymbol{k}_0^i) + \varepsilon_n^{i'}(\boldsymbol{k}_0^i) + \varepsilon_n^{i''}(\boldsymbol{k}_0^i) = \varepsilon_n^i(\boldsymbol{k}_0^i) + U_{\boldsymbol{k}_0^i} + \frac{\hbar^2(k^2-k_0^{i2})}{2m_0} + \frac{\hbar}{m_0}(\boldsymbol{k}-\boldsymbol{k}_0^i)\cdot\boldsymbol{p}_{nn'}(\boldsymbol{k}_0^i) + \frac{\hbar^2}{m_0^2}\sum_{n'\neq n}\frac{(\boldsymbol{k}-\boldsymbol{k}_0^i)\cdot\boldsymbol{p}_{nn'}(\boldsymbol{k}_0^i)(\boldsymbol{k}-\boldsymbol{k}_0^i)\cdot\boldsymbol{p}_{n'n}(\boldsymbol{k}_0^i)}{\varepsilon_n^i(\boldsymbol{k}_0^i)-\varepsilon_{n'}^i(\boldsymbol{k}_0^i)}, \quad (15)$$

where

$$\begin{aligned}\varepsilon_n^{i''}(\boldsymbol{k}_0^i) = &\sum_{n'\neq n}\left\{\frac{\hbar}{m_0}(\boldsymbol{k}-\boldsymbol{k}_0^i)\cdot\boldsymbol{p}_{nn'}(\boldsymbol{k}_0^i) + \Big[\frac{\hbar^2(\boldsymbol{k}^2-\boldsymbol{k}_0^{i2})}{2m_0} + U_{\boldsymbol{k}_0^i}\Big]\delta_{nn'}\right\}\\ &\times\left\{\frac{\hbar}{m_0}(\boldsymbol{k}-\boldsymbol{k}_0^i)\cdot\boldsymbol{p}_{n'n}(\boldsymbol{k}_0^i) + \Big[\frac{\hbar^2(\boldsymbol{k}^2-\boldsymbol{k}_0^{i2})}{2m_0} + U_{\boldsymbol{k}_0^i}\Big]\delta_{n'n}\right\} \div \Big[\varepsilon_n^i(\boldsymbol{k}_0^i) - \varepsilon_{n'}^i(\boldsymbol{k}_0^i)\Big]\\ = &\frac{\hbar^2}{m_0^2}\sum_{n'\neq n}\frac{(\boldsymbol{k}-\boldsymbol{k}_0^i)\cdot\boldsymbol{p}_{nn'}(\boldsymbol{k}_0^i)(\boldsymbol{k}-\boldsymbol{k}_0^i)\cdot\boldsymbol{p}_{n'n}(\boldsymbol{k}_0^i)}{\varepsilon_n^i(\boldsymbol{k}_0^i)-\varepsilon_{n'}^i(\boldsymbol{k}_0^i)}. \end{aligned} \quad (16)$$

A comparison between expression (15) and one of unstrained Si shows that the strained and unstrained Si have an identical CB dispersion relation in addition to an added constant term, $U_{\boldsymbol{k}_0^i}$. This means that Δ^i levels in the strained Si will be different from Δ_1 level in the unstrained Si, which is attributed to the two facts: (1) Varying $\boldsymbol{k}$ in the vicinity of $\boldsymbol{k}_0^i$, the deformation potential fields are taken as constants, independent of K wavevector. Therefore, all Δ^i valleys shift rigidly under the lattice deformation. That is,

all points in the vicinity of a valley minimum shift by the same account. Thus, the shape of the valley is preserved and the position of the extremal point $\boldsymbol{k}_0^i$ is unaltered, which are placed at a distance of $(0.85 \pm 0.03)2\pi/a$ away from the Γ point to Δ direction; (2) The CB states without any strain perturbation which are degenerate in energy have significantly different wavevectors, so, for any specific wavevector, no pair of CB states under the strain perturbation is degenerate or very close to each other in energy. This means that any coupling between them is insignificant, and therefore may be neglected. So, band index n sampling in the term $\varepsilon_n^{i''}(\boldsymbol{k}_0^i)$ in expression (15) has no difference from the one for the unstrained situation.

It is convenient to transform Eq.(15) into our familiar form for the discussion of effective mass. Because the point $\boldsymbol{k}_0^i$ is extremal, the condition $(\nabla_{\boldsymbol{k}}\varepsilon_n^i)_{\boldsymbol{k}=\boldsymbol{k}_0^i} = 0$ from Eq.(10) gives

$$\boldsymbol{p}_{nn'}(\boldsymbol{k}_0^i) + \hbar\boldsymbol{k}_0^i = 0. \tag{17}$$

By using this relation, we can obtain from expression (15) the following expression for energy in the vicinity of extremal point $\boldsymbol{k}_0^i$:

$$\varepsilon_n^i(\boldsymbol{k}) = \varepsilon_n^i(\boldsymbol{k}_0^i) + U_{\boldsymbol{k}_0^i} + \frac{\hbar^2}{2}\sum_{\alpha,\beta=1}^{3}\Big(\frac{1}{m_{\alpha\beta}^i}\Big)_n \times (k_\alpha^i - k_{0\alpha}^i)(k_\beta^i - k_{0\beta}^i), \tag{18}$$

where quantities $(1/m_{\alpha\beta}^i)_n$ are given by the relation

$$\Big(\frac{1}{m_{\alpha\beta}^i}\Big)_n = \frac{\delta_{\alpha\beta}}{m_0} + \frac{2}{m_0^2}\sum_{n'\neq n}\frac{p_{nn'}^\alpha(\boldsymbol{k}_0^i)p_{n'n}^\beta(\boldsymbol{k}_0^i)}{\varepsilon_n^i(\boldsymbol{k}_0^i) - \varepsilon_{n'}^i(\boldsymbol{k}_0^i)} \tag{19}$$

with $p_{nn'}^\alpha(\boldsymbol{k}_0^i)$ bing the αth component of $\boldsymbol{p}_{nn'}(\boldsymbol{k}_0^i)$ (the indices α and β denote the co-ordinates x, y, z). So, we have the constant-energy equation near the Δ^i valley under strain

$$\varepsilon^i(\boldsymbol{k}) = \varepsilon_{\rm c}(\boldsymbol{k}_0) + \Delta\varepsilon_{\rm c}^i + \frac{\hbar^2}{2}\Big[\frac{(k_x - k_{0x}^i)^2}{m_x^*} + \frac{(k_x - k_{0y}^i)^2}{m_y^*} + \frac{(k_x - k_{0z}^i)^2}{m_z^*}\Big]. \tag{20}$$

Noting expression (15), constant-energy expression (20) equivalent to expression (15) shows that the effective mass components in Eq.(20) are the same as ones of unstrained Si, which can be represented as two significant 'effective' masses to describe the shape of the energy ellipsoid—namely, the longitudinal and transverse masses ($m_{\rm l}^*$ and $m_{\rm t}^*$).

4. Calculation of energy shift

As it has been pointed out in the previous section, Δ^i level in strained Si is different from Δ_1 level in unstrained Si. The strain-induced energy shift ($\Delta\varepsilon_{\rm c}^i$) between them may be determined by the deformation potential theory. The formulae are as follows:[11]

$$\varepsilon_\parallel = (a_{{\rm Si}_{1-x}{\rm Ge}_x} - a_{\rm Si})/a_{\rm Si}, \tag{21}$$

for the (001) substrate:

$$\varepsilon_{xx} = \varepsilon_{yy} = \varepsilon_\parallel, \quad \varepsilon_{zz} = -\varepsilon_\parallel/\sigma^{(001)}, \tag{22}$$

$$\Delta\varepsilon_{\rm c}^{(100)} = \Delta\varepsilon_{\rm c}^{(00\bar{1})} = \Xi_{\rm d}^\Delta(\varepsilon_{xx}+\varepsilon_{yy}+\varepsilon_{zz}) + \Xi_u^\Delta\varepsilon_{zz}; \tag{23}$$

for the (111) substrate:

$$\varepsilon_{xx} = \varepsilon_{yy} = \varepsilon_{zz} = \frac{1}{3}\Big[2 - 1/\sigma^{(111)}\Big]\varepsilon_\parallel, \tag{24}$$

$$\Delta\varepsilon_{\rm c}^{(100)} = \Delta\varepsilon_{\rm c}^{(\bar{1}00)} = \Delta\varepsilon_{\rm c}^{(010)} = \Delta\varepsilon_{\rm c}^{(0\bar{1}0)} = \Delta\varepsilon_{\rm c}^{(001)} = \Delta\varepsilon_{\rm c}^{(00\bar{1})} = \Xi_{\rm d}^\Delta(\varepsilon_{xx}+\varepsilon_{yy}+\varepsilon_{zz}) + \Xi_u^\Delta\varepsilon_{xx}; \tag{25}$$

for the (101) substrate:

$$\varepsilon_{xx} = \varepsilon_{zz} = \frac{1}{2}[1 - 1/\sigma^{(101)}]\varepsilon_\parallel, \quad \varepsilon_{yy} = \varepsilon_\parallel, \tag{26}$$

$$\Delta\varepsilon_{\rm c}^{(100)} = \Delta\varepsilon_{\rm c}^{(\bar{1}00)} = \Delta\varepsilon_{\rm c}^{(001)} = \Delta\varepsilon_{\rm c}^{(00\bar{1})} = \Xi_{\rm d}^\Delta(\varepsilon_{xx} + \varepsilon_{yy} + \varepsilon_{zz}) + \Xi_u^\Delta\varepsilon_{xx}. \tag{27}$$

Values of parameters used in calculation are listed in Table 1. Substituting those values into the above formulae, the strain-induced energy shift is determinable. The results are shown in Fig.4.

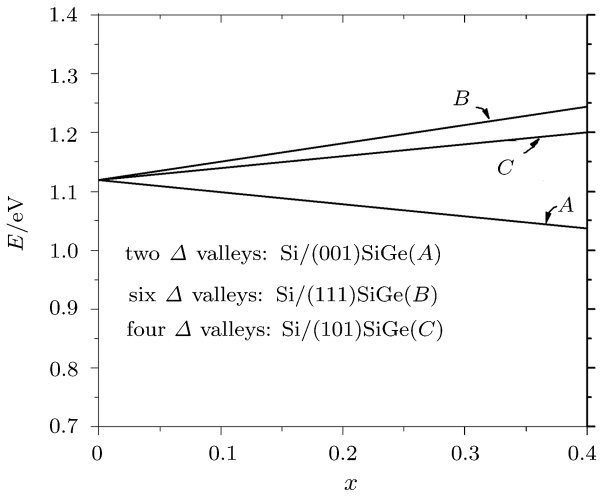


Fig.4. Δ levels versus X in TS-Si on ${\rm Si}_{1-x}{\rm Ge}_x$.

Table 1. Values[10] of parameters used in calculation.

Parameter	Symbol	Value
Si lattice constant	a_0/Å	5.4309
Ge lattice constant	a_0/Å	5.6579
Poisson's ratio	$\sigma^{(001)}$	1.296
Poisson's ratio	$\sigma^{(111)}$	2.275
Poisson's ratio	$\sigma^{(101)}$	1.959
Dilatation DP	$\Xi_{\rm d}^{\Delta}$/eV	1.75
Shear DP	Ξ_{u}^{Δ}/eV	9.16

5. Conclusion

We have systematically investigated the features of CB of TS-Si/$Si_{1-x}Ge_x$ that are needed for quantitative transport calculations, namely the number of equivalent CB edge energy extrema, CB energy minima, the position of the extremal point, and effective mass. The main results of this paper can be deduced from Figs.1–4 and expression (20). Noticeably, strained and unstrained materials have the same values of CB effective mass derived by using the K·P method, which are in good accordance with those cited from other references.

References

[1] Hu H Y, Zhang H M, Jia X Zh, Dai X Y and Xuan R X 2007 *Chinese Journal of Semiconductors* **28** 36

[2] Shu Zh Y and Yang H D 2006 *Chin. Phys.* **15** 1374

[3] Chakraborty S, Bera M K, Bhattacharya S, Bose P K and Maiti C K 2006 *Thin Solid Films* **504** 73

[4] Guillaume T and Mouis M 2006 *Solid-State Electronics* **50** 701

[5] Hu H Y, Zhang H M, Dai X Y and Lü Y 2004 *Chin. Phys.* **12** 295

[6] Shu B, Dai X Y and Zhang H M 2004 *Chin. Phys.* **13** 235

[7] Rieger M, Vogl P 1993 *Phys. Rev.* **48** 276

[8] Dhar S, Kosina H, Palankovski V, Ungersboeck S E and Selberherr S 2005 *IEEE Transactions On Electron Devices* **52** 527

[9] Xie X D and Lu D 1998 *Energy Band Theory of Solids* (Shanghai: Fudan University Press) 58-62 (in Chinese)

[10] Fischetti M V and Laux S E 1996 *Appl. Phys.* **80** 2234

[11] Smirnov S and Kosina H 2004 *Solid-State Electronics* **48** 1325