Physics and Engineering of CMOS Devices

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Resistance Change due to Strain

Piezoresistance Coefficient

$\left(\Delta \rho_{\rm l} / \rho_{\rm l} \right)$		(π_{11})	π_{12}	$\pi_{_{12}}$	0	0	0)	(σ_1)
$\Delta ho_2/ ho_2$		π_{12}	π_{11}	π_{12}	0	0	0	σ_2
$\Delta ho_3 / ho_3$		π_{12}	π_{12}	π_{11}	0	0	0	σ_{3}
$\Delta ho_4/ ho_4$	_	0	0	0	$\pi_{_{44}}$	0	0	$\sigma_{_4}$
$\Delta ho_5/ ho_5$		0	0	0	0	$\pi_{_{44}}$	0	$\sigma_{_{5}}$
$\left(\Delta ho_{6} / ho_{6}\right)$		0	0	0	0	0	$\pi_{_{44}}$	$\left(\sigma_{_{6}} ight)$

Material	n-Si	p-Si	
ρ (Ωcm)	11.7	7.8	
$\pi_{11} (10^{-12} \text{ cm}^2/\text{dyne})$	-102.2	+6.6	
π_{12} (10 ⁻¹² cm ² /dyne)	53.4	-1.1	
π_{44} (10 ⁻¹² cm ² /dyne)	-13.6	+138.1	

Piezoresistance coefficient is material parameters for bulk Si. However, it can be used to estimate MOSFET resistance change.

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例: Local Strain (Uniaxial Stress)



Mobility change by uniaxial stress



K. Uchida et al., IEDM, p229, 2004.

At low field, piezoresistance coefficeint is a good predictor of mobility enhancement. However, at high field discrepancy becomes large.

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例: Global Strain (Biaxial Stress) - Electron -

Mobility change due to biaxial stress



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Band structure change due to stress

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Deformation Potential

Taylor expansion

$$\Delta E_{c} = \frac{\partial E}{\partial \varepsilon_{xx}} \varepsilon_{xx} + \frac{\partial E}{\partial \varepsilon_{yy}} \varepsilon_{yy} + \frac{\partial E}{\partial \varepsilon_{zz}} \varepsilon_{zz} + \frac{\partial E}{\partial \varepsilon_{xy}} \varepsilon_{xy} + \frac{\partial E}{\partial \varepsilon_{yz}} \varepsilon_{yz} + \frac{\partial E}{\partial \varepsilon_{zx}} \varepsilon_{zx} + \dots$$

ひずみテンソルの要素数が6つであるこ
とに対応して、エネルギー変化を表す係
数は6つ必要。シリコンの場合には結晶
の対称性のため、2つでOK.
$$E_{d} = \frac{1}{2} \left(\frac{\partial E}{\partial \varepsilon_{yy}'} + \frac{\partial E}{\partial \varepsilon_{zz}'} \right)$$

$$E_{u} = \frac{\partial E}{\partial \varepsilon_{xx}'} - E_{d}$$

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Deformation Potential

Herring and Vogt have expressed the energy change due to a strain as a Hamiltonian of the form

$$H_{HV} = \Xi_d \left(\operatorname{Tr} \{ \mathbf{e} \} \right) + \Xi_u \left(\hat{\mathbf{k}} \cdot \mathbf{e} \cdot \hat{\mathbf{k}} \right)$$

 $\hat{\bf k}$ is a unit vector along the direction of one of the equivalent [100] conduction band minima in reciprocal space.

$$\Xi_d \approx 5 \,\mathrm{eV}$$
$$\Xi_u = 8.77 \,\mathrm{eV}$$

P. Yu and M. Cardona, Fundamentals of Semiconductors, 3rd ed., Springer 1998.

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Energy Change for Each Valley

$$\begin{bmatrix} 100 \end{bmatrix}, \begin{bmatrix} 1'00 \end{bmatrix} \\ \Delta E^{100} = \Xi_d \left(\varepsilon_{xx}' + \varepsilon_{yy}' + \varepsilon_{zz}' \right) + \Xi_u \varepsilon_{xx}' \\ \begin{bmatrix} 010 \end{bmatrix}, \begin{bmatrix} 01'0 \end{bmatrix} \\ \Delta E^{010} = \Xi_d \left(\varepsilon_{xx}' + \varepsilon_{yy}' + \varepsilon_{zz}' \right) + \Xi_u \varepsilon_{yy}' \\ \begin{bmatrix} 001 \end{bmatrix}, \begin{bmatrix} 001' \end{bmatrix} \\ \Delta E^{001} = \Xi_d \left(\varepsilon_{xx}' + \varepsilon_{yy}' + \varepsilon_{zz}' \right) + \Xi_u \varepsilon_{zz}' \end{bmatrix}$$

Split of 6-fold Degenracy

Global Strain (Biaxial Stress)の場合



x,y方向のBiaxial Stressであれば、 $\varepsilon_{xx} = \varepsilon_{yy} != \varepsilon_{zz}$ なので [100], [1'00], [010], [01'0]の4重縮退 [001], [001']の2重縮退

Local Strain (Uniaxial Stress)の場合



x方向のUniaxial Stressであれば、 $\varepsilon_{xx} \mathrel{!=} \varepsilon_{yy} = \varepsilon_{zz}$ なので [100], [1'00]の2重縮退 [010], [01'0], [001], [001']の4重縮退

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例: Global Strain (Biaxial Stress)



Si_{1-x}Ge_x Virtual SubstrateのGe content xとひず ε_{xx} の間には $\varepsilon_{xx} \sim 0.04x$ の関係がある。 従って、2重縮退と4重縮退のエネルギー差 ΔE は $\Delta E \sim 0.62x$ eVの関係がある。