Lecture11

# Physics and Engineering of CMOS Devices

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Physics and Engineering of CMOS Devices, Ken Uchida, Tokyo Tech, June 30, 2010

## **Resistance Change due to Strain**

## **Piezoresistance Coefficient**

$\left( \Delta \rho_{\rm l} / \rho_{\rm l} \right)$		$(\pi_{11})$	$\pi_{12}$	$\pi_{12}$	0	0	0 )	$(\sigma_1)$
$\Delta ho_2/ ho_2$		$\pi_{12}$	$\pi_{11}$	$\pi_{\scriptscriptstyle 12}$	0	0	0	$\sigma_2$
$\Delta  ho_3 /  ho_3$	_	$\pi_{12}$	$\pi_{12}$	$\pi_{11}$	0	0	0	$\sigma_{3}$
$\Delta ho_4/ ho_4$	-	0	0	0	$\pi_{_{44}}$	0	0	$\sigma_{_4}$
$\Delta ho_5/ ho_5$		0	0	0	0	$\pi_{_{44}}$	0	$\sigma_{_{5}}$
$\left(\Delta ho_{6}/ ho_{6} ight)$		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	
$\pi_{12}$ (10 <sup>-12</sup> cm <sup>2</sup> /dyne)	53.4	-1.1	
$\pi_{44}$ (10 <sup>-12</sup> cm <sup>2</sup> /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.

## 例: Global Strain (Biaxial Stress) - Electron -

Mobility change due to biaxial stress



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1.5

1.0

0

10

20

30

Electron

40

Equivalent [Ge] in Fully Relaxed SiGe (%) K. Rim *et al.*, *IEDM*, p47, 2003.

Bulk <sub>●</sub> N<sub>D</sub>=4x10<sup>16</sup>cm<sup>-3</sup>

0 1

Effective Field [MV/cm]

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

50



### 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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10

#### **Deformation Potential**

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

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

 $\hat{\bf k}$  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, 3<sup>rd</sup> 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





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、  $\varepsilon_{xx} \coloneqq \varepsilon_{yy} = \varepsilon_{zz}$ 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<sub>1-x</sub>Ge<sub>x</sub> Virtual SubstrateのGe content xとひず $\varepsilon_{xx}$ 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 $\Delta E$ は $\Delta E \sim 0.62x$  eVの関係がある。