Single-Event Transients in Strained-Si Devices

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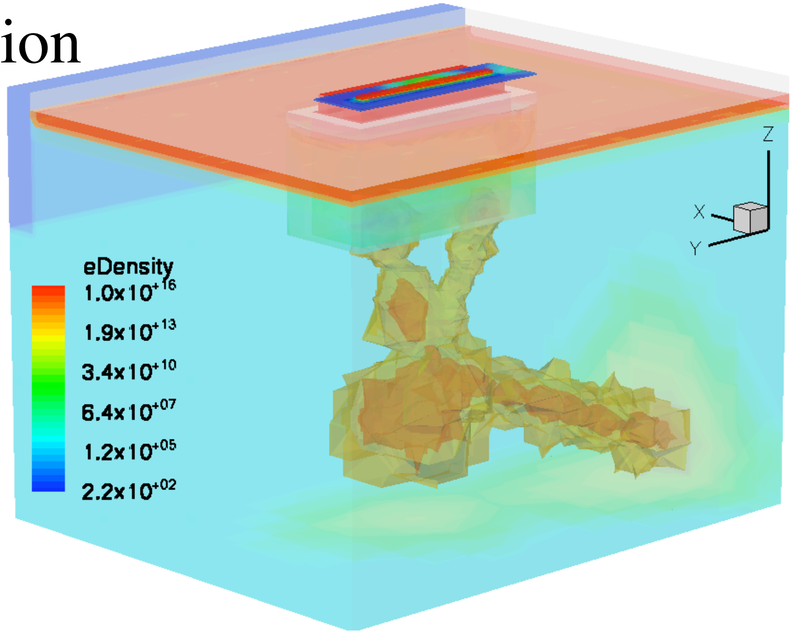
Objectives

- Provide device simulation environment for rad-hard applications
- Address Rad-Hard specific issues
  - Physics - strain
  - Numerics - automatic operation
  - Coupled Device / Defect



Outline

- Background - FLOODS Code
- Numeric Issues and Enhancements
- Physical Issues and Enhancements
- Conclusions

FLOOPS / FLOODS

- Multi-dimensional, Object-oriented codes
- P = Process / D = Device 90% code shared
- Scripting capability for PDE's - Alagator

- Commercialized - ISE / Synopsis
  - Sentaurus - Process is based on FLOOPS

- Licensed at over 300 sites world-wide

What is Alagator?

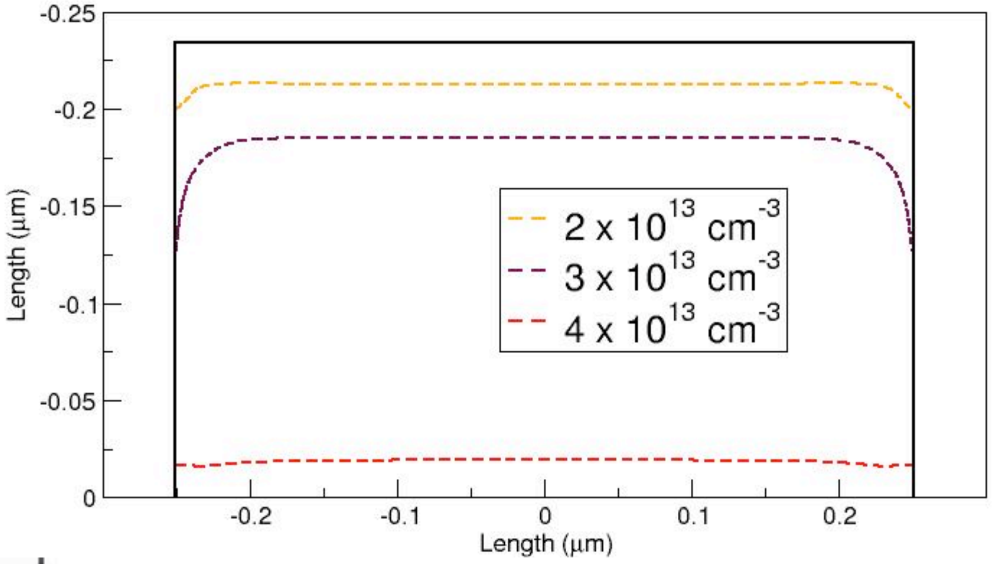
Operator	***Description***
“ddt”	Time derivative
“grad”	Spatial derivative
“sgrad”	Scharfetter / Gummel Discretization Operator
“dot”	Returns the dot product of the gradient of two scalar arguments
“elastic”	Compute elastic forces - FEM balance
“EffMass”	Computes the effective mass change as a function of strain and current direction

- Example use of operators for diffusion equation
- Fick’s Second Law of Diffusion
  - ddt(Boron) - 9.0e-16 * grad(Boron)
  - $\partial C(x,t) / \partial t = D \partial^2 C(x,t) / \partial x^2$
- All physics is defined on the command line
- Rapidly evolve models for new devices / materials / physics

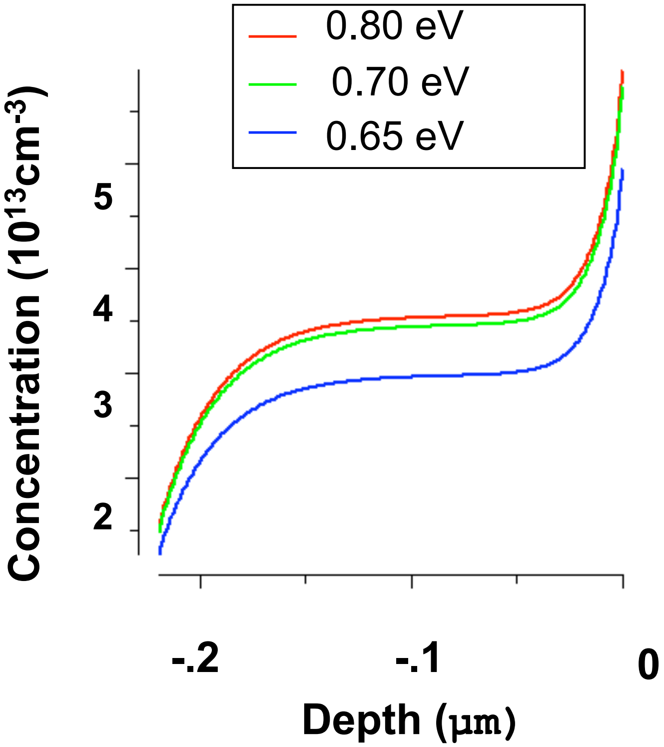
Collaboration

$$\frac{\partial p_t}{\partial t} = \sigma_{N_t} v_{th,p} p N_t - \frac{p_t}{\tau_{p_t}}$$

$$\frac{1}{\tau_{p_t}} = N_v \sigma v_{th} \exp(-\frac{E_t}{kT})$$



Trapped hole concentrations for E_t=0.8 eV



Slice down x=0 for all energy levels

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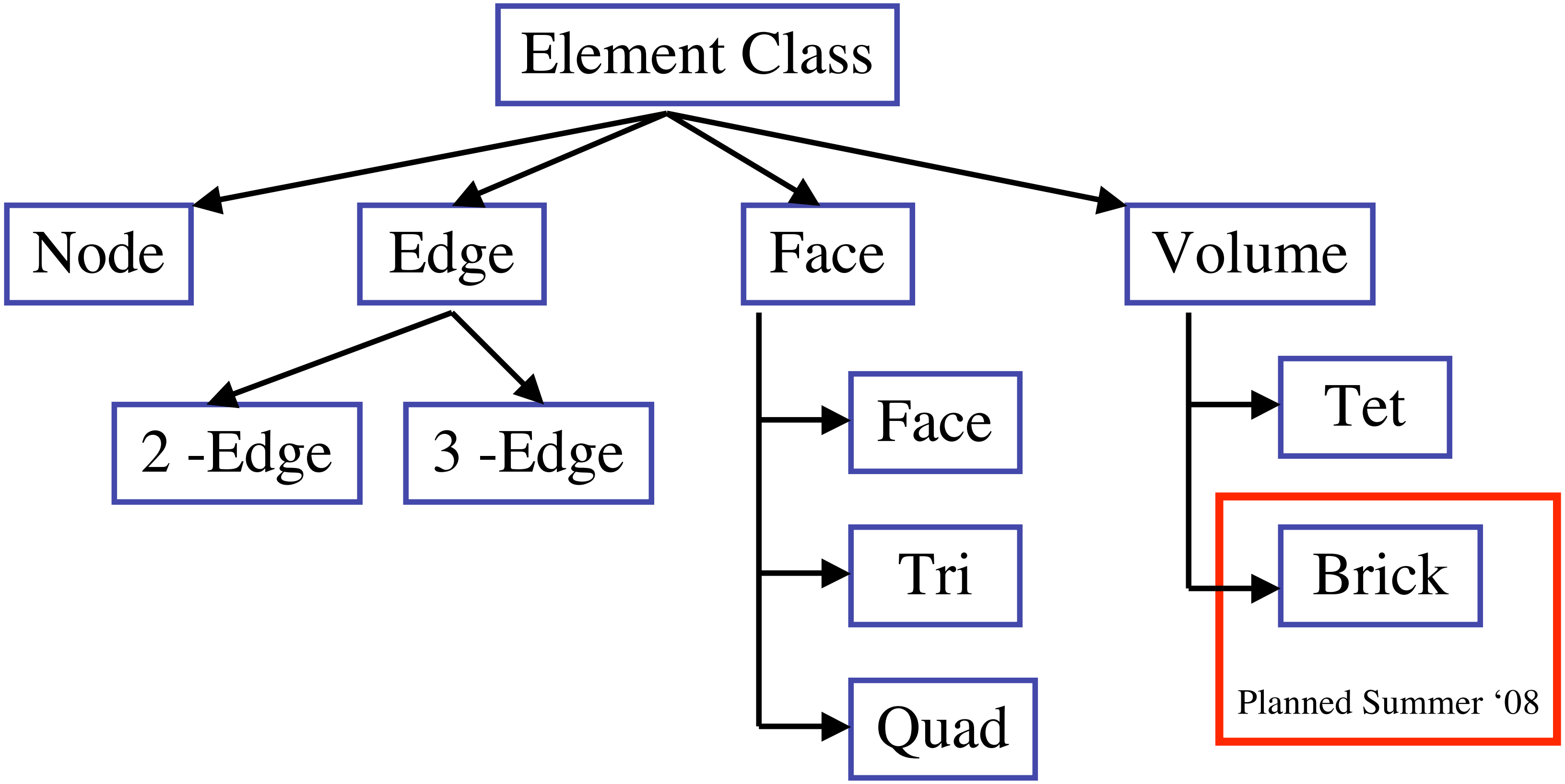
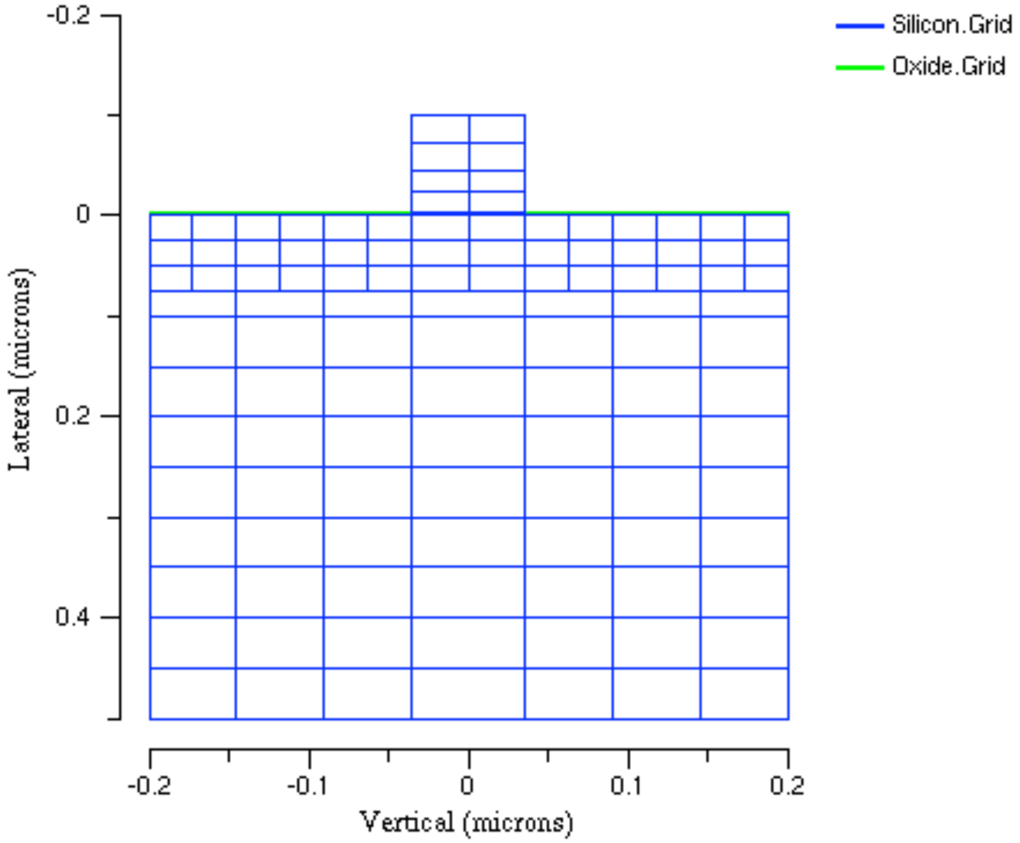
Object Oriented

- Derived Specific Geometry Elements
- Common properties so code is independent



Anisotropic Grid - Mixed Elements



- For many reasons, quads are better shapes for device simulation
- Rectangular region created at the command line
- Refinement creates mixed elements and terminated lines
- Assembly runs on generalized elements

Parallel Element based Assembly

- Working toward a fully element based assembly
  - Current split operators among grid pieces
  - Each assembled separately
  - Lots of matrix loads - parallel conflict
- Fewer parallel conflicts with Matrix Load
  - Assemble all element pieces together
  - Single load per element to Matrix
- Fewer Matrix Load Operations
  - Might be beneficial on scalar processors
- Compatible with public domain grid partitioning
  - Partition grid regions and data along slices

Elastic Assembly - Element Assembly

- Data Comes from ElementInfo Class
- All are vectors - 128 long
- Code Fragment of Assembly

```
for(i = 0; i < BDim; i++) {
    for(j = 0; j < BDim; j++) {
          sij = 0.0;
          for(l = 0; l < Ddim; l++) {
               for(k = 0; k < Ddim; k++) {
                    //multiply BT, D, B
                  sij.MultSum(ev.BM(k,i),ev.BM(l,j), dval[D[k][l]]);
               }
         }
         sij *= ev.Size();
    }
}
```

D Matrix Spatially Varying

$$[6x6] = [6x3] \cdot [3x3] \cdot [3x6]$$

$$k^e = B^T \cdot D \cdot B \cdot \Delta$$

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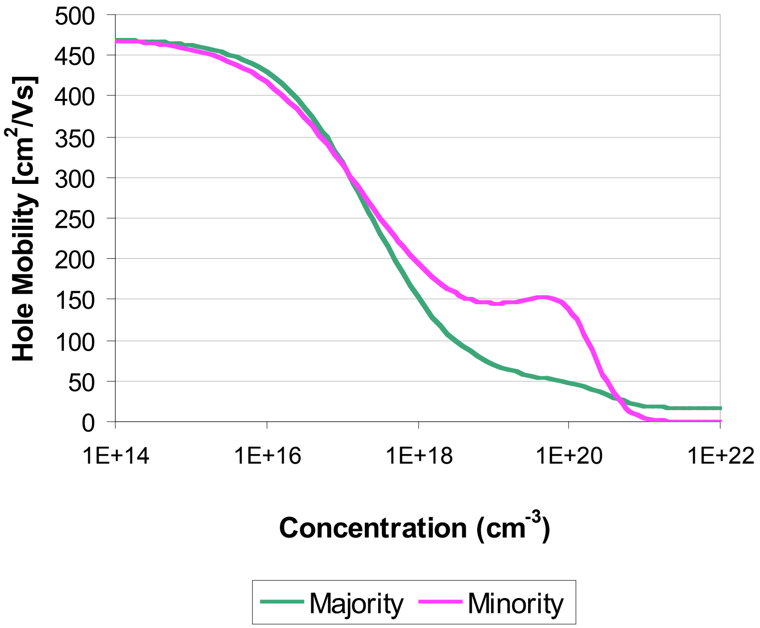
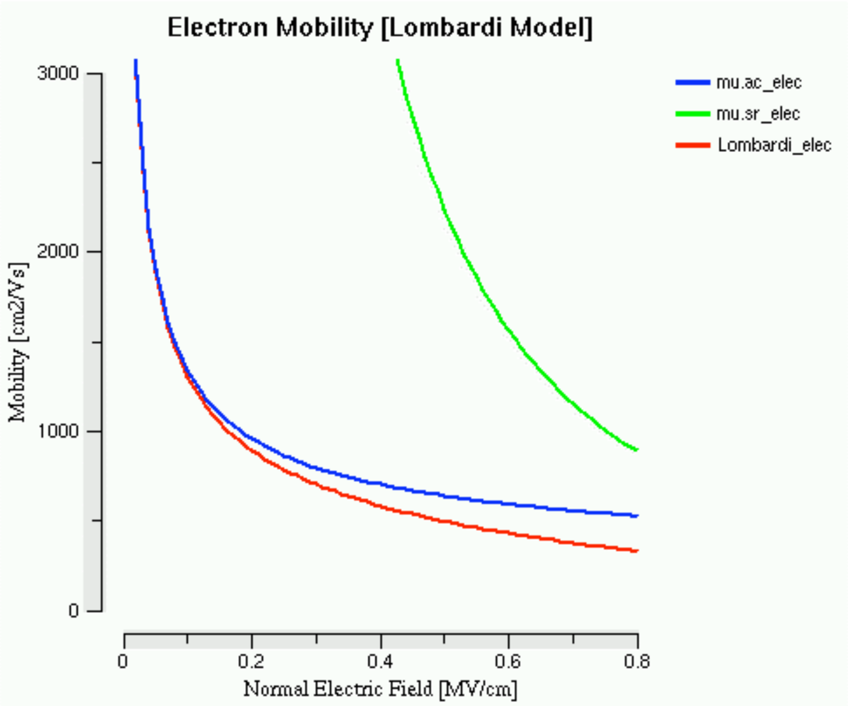
Complex Mobility Model Available



Unifies the description of majority and minority carrier bulk mobilities

- temperature dependence
- electron–hole scattering
- screening of ionized impurities by carriers
- clustering of impurities

Surface scattering terms (Vertical Field)
Velocity Saturation
EffMass changes w/ strain (more later)



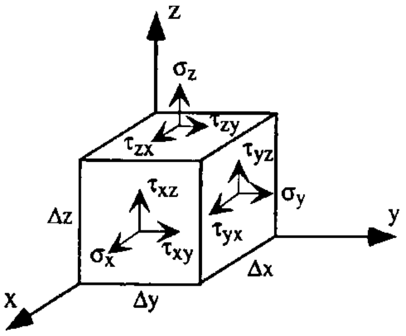
Piezoresistance

- Piezoresistivity is the change in electrical resistivity with mechanical stress and involves the relationships between electric field E_i, current density J_j, and mechanical stress σ_{kl}

$$E_i = \left(\rho_{ij} + \Pi_{ijkl}\sigma_{kl}\right)J_j$$

(Small Change Limit)

$$\underbrace{\begin{bmatrix} -\Delta\mu_{xx}/\mu_{xx} \\ -\Delta\mu_{yy}/\mu_{yy} \\ -\Delta\mu_{zz}/\mu_{zz} \\ -\Delta\mu_{yz}/\mu_{yz} \\ -\Delta\mu_{zx}/\mu_{zx} \\ -\Delta\mu_{xy}/\mu_{xy} \end{bmatrix}}_{\text{Mobility Change}} = \underbrace{\begin{bmatrix} \Delta\rho_{xx}/\rho_{xx} \\ \Delta\rho_{yy}/\rho_{yy} \\ \Delta\rho_{zz}/\rho_{zz} \\ \Delta\rho_{yz}/\rho_{yz} \\ \Delta\rho_{zx}/\rho_{zx} \\ \Delta\rho_{xy}/\rho_{xy} \end{bmatrix}}_{\text{Resistivity Change}} = \underbrace{\begin{bmatrix} \pi_{11} & \pi_{12} & \pi_{12} & 0 & 0 & 0 \\ \pi_{12} & \pi_{11} & \pi_{12} & 0 & 0 & 0 \\ \pi_{12} & \pi_{12} & \pi_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & \pi_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & \pi_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & \pi_{44} \end{bmatrix}}_{\text{Piezoresistance coefficients}} \underbrace{\begin{bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{zz} \\ \sigma_{yz} \\ \sigma_{zx} \\ \sigma_{xy} \end{bmatrix}}_{\text{Stress components}}$$



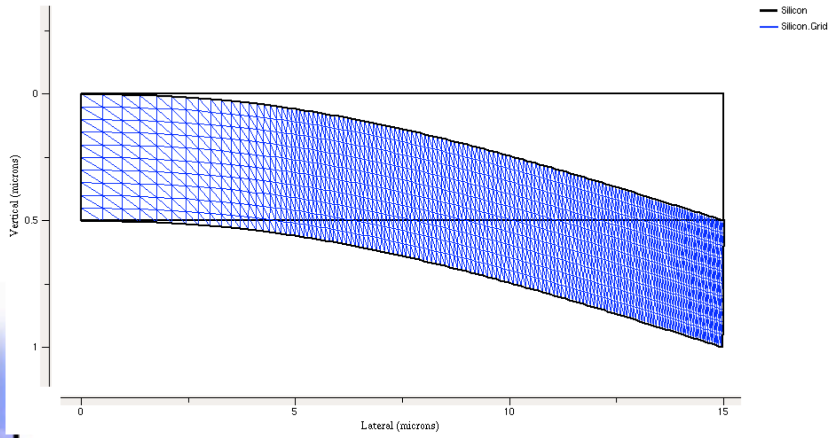
$$J_{n,p} = -qn\mu_{n,p}\nabla\phi_{n,p}$$

$$\begin{bmatrix} J_X(\sigma) \\ J_Y(\sigma) \\ J_Z(\sigma) \end{bmatrix} = \begin{bmatrix} 1-\Delta\mu_{xx}/\mu_{xx} & -\Delta\mu_{xy}/\mu_{xy} & -\Delta\mu_{zx}/\mu_{zx} \\ -\Delta\mu_{xy}/\mu_{xy} & 1-\Delta\mu_{yy}/\mu_{yy} & -\Delta\mu_{yz}/\mu_{yz} \\ -\Delta\mu_{zx}/\mu_{zx} & -\Delta\mu_{yz}/\mu_{yz} & 1-\Delta\mu_{zz}/\mu_{zz} \end{bmatrix} \begin{bmatrix} J_X(0) \\ J_Y(0) \\ J_Z(0) \end{bmatrix}$$

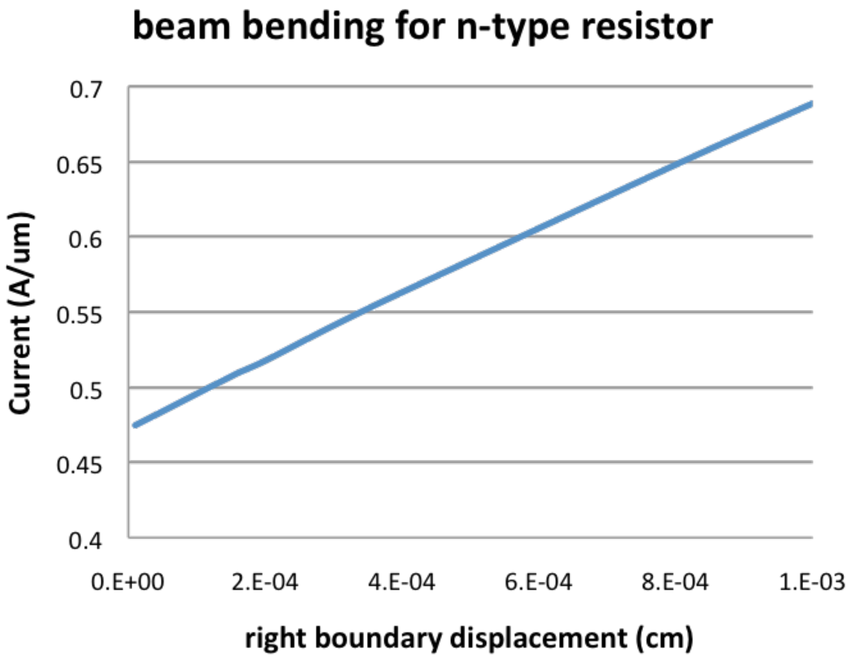
Piezoresistance example

- Silicon beam with an n-type surface
- Bending induces tensile stress at the surface resulting in a increase in mobility and current.

$$J_X(\sigma) \cong \left(1 + \underset{(+)}{\frac{-\Delta\mu_{xx}}{\mu_{xx}}}\right) J_X(0) = \left(1 + \underset{(-)}{\pi_{11}}\underset{(+)}{\sigma_{xx}}\right) J_X(0)$$



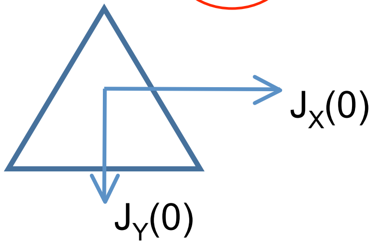
FLOOXS beam bending example



Piezoresistance

- The gradient of the quasi-fermi level gives $J_{n,p}$ vector values for each element

$$J_{n,p} = -qn\mu_{n,p}\boxed{\nabla\phi_{n,p}}$$

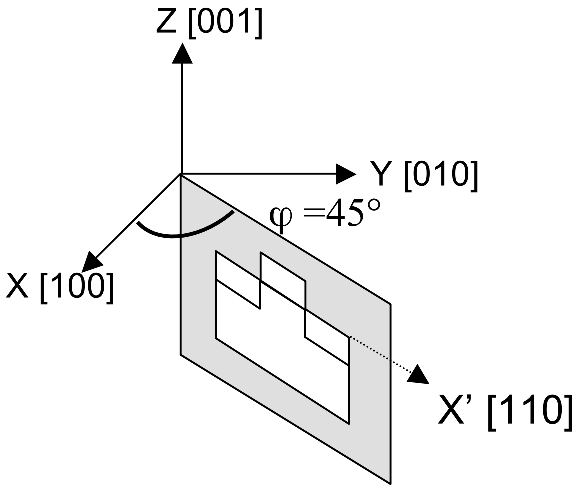


$$\begin{bmatrix} J_X(\sigma) \\ J_Y(\sigma) \end{bmatrix} = \begin{bmatrix} 1-\Delta\mu_{xx}/\mu_{xx} & -\Delta\mu_{xy}/\mu_{xy} \\ -\Delta\mu_{xy}/\mu_{xy} & 1-\Delta\mu_{yy}/\mu_{yy} \end{bmatrix} \begin{bmatrix} J_X(0) \\ J_Y(0) \end{bmatrix}$$

- Piezoresistance coefficient matrix can be defined for any orientation using directional cosines

$$\pi_{ijkl}' = \sum_m \sum_n \sum_o \sum_p a_{mi} a_{nj} a_{ok} a_{pl} \pi_{mnop}$$

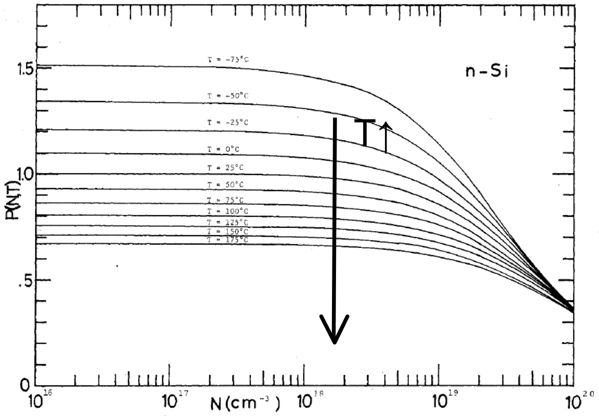
$$\begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} = \begin{bmatrix} \cos\phi\cos\theta & -\sin\phi & \cos\phi\sin\theta \\ \sin\phi\cos\theta & \cos\phi & \sin\phi\sin\theta \\ -\sin\theta & 0 & \cos\theta \end{bmatrix}$$



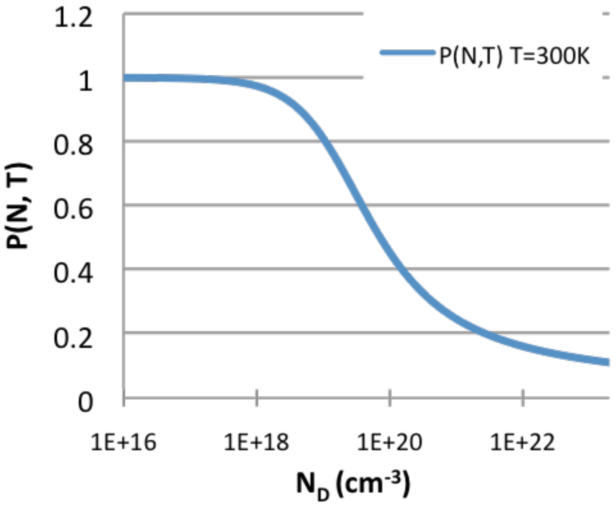
Piezoresistance

- Piezoresistance coefficients can be set to spatially vary in FLOODS
  - Extracted channel and bulk coefficients different (to do)
- Piezoresistance coefficients are function of impurity concentration and temperature P(N,T)

$$P_{n,p}(N,T) = \frac{300}{T}\frac{F'_{s+(1/2)}\left(E_{F_{n,p}}/(k_B T)\right)}{F_{s+(1/2)}\left(E_{F_{n,p}}/(k_B T)\right)}$$



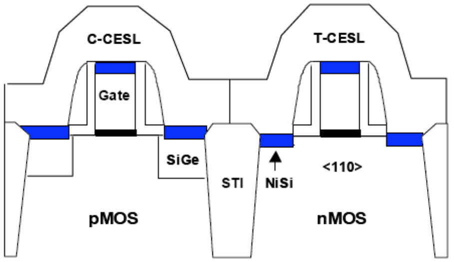
Kanda Y., IEEE Trans Electron Devices 1987



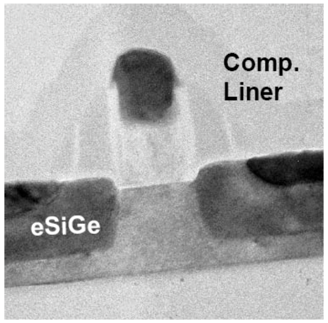
FLOODS predicted piezoresistance factor for T=300 K

Strained PMOS

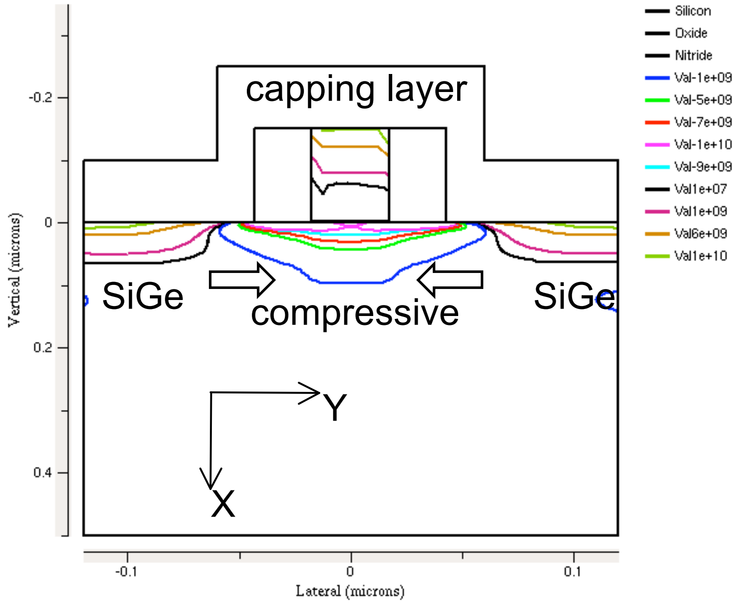
- To enhance channel mobility, PMOS strain processing includes embedded SiGe in the source/drain regions and compressive capping layers.
- FLOOXS predicts strain/stress profiles where the channel stress is ~1 GPa



Cheng, *et al.* IEDM 2007



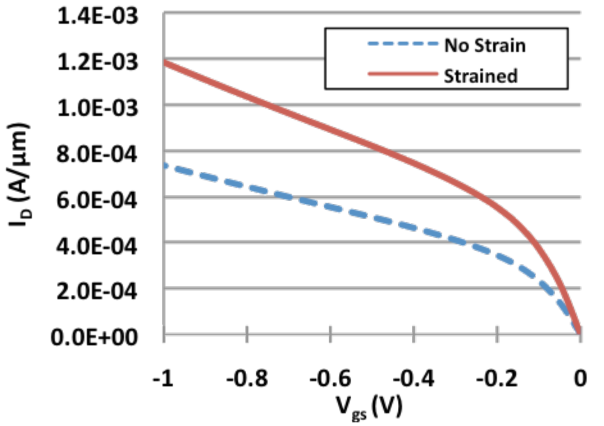
Horstmann, *et al.* IEDM 2005

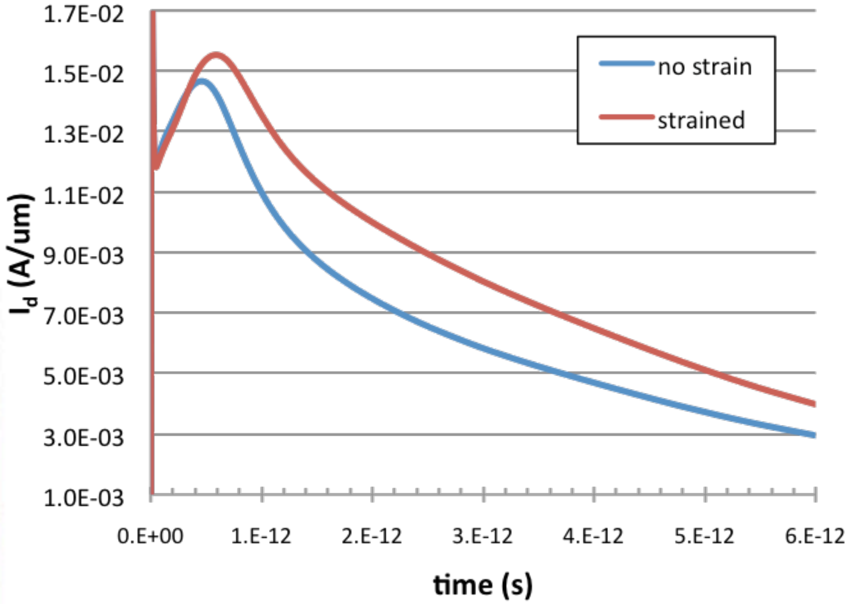


FLOOXS predicted stress profile [dyne/cm2]
(YY component - channel direction)

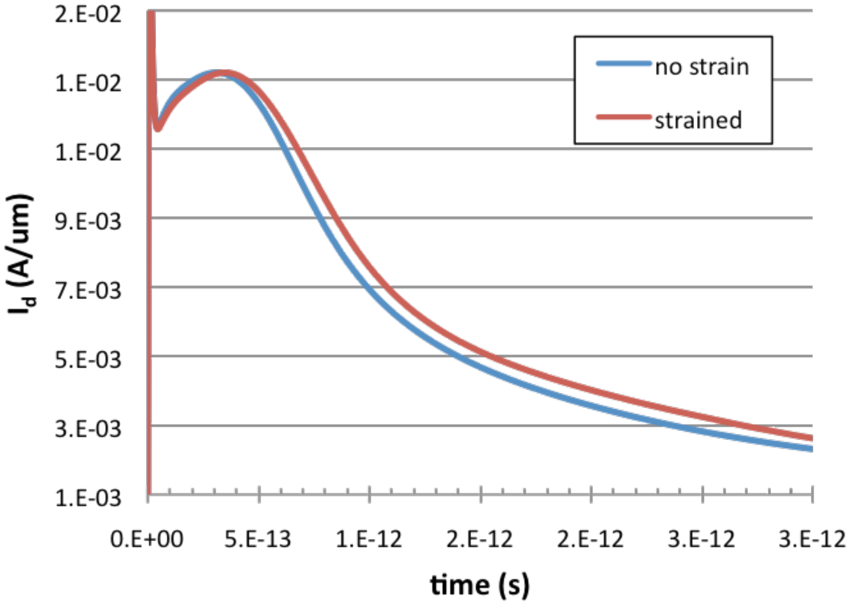
Strained PMOS Simulations

- PMOS with L_{gate}=30 nm
- <110> channel orientation
- 2007 ITRS dimensions
- Charge strike dist. in drain





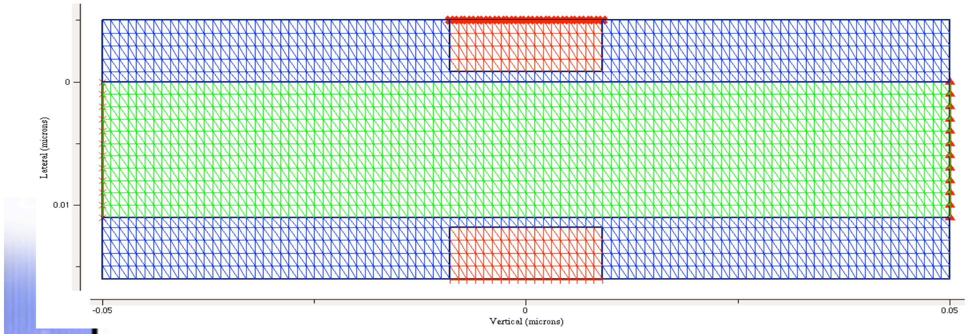
PMOS Current Transient (V_{gs}=-1.0 V, V_{ds}=-1.0 V)



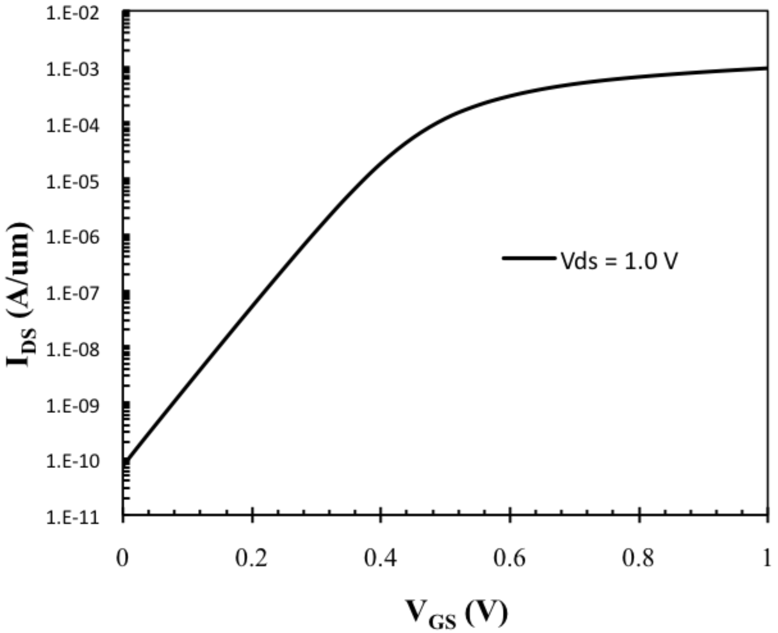
PMOS Current Transient (V_{gs}=0 V, V_{ds}=-1.0 V)

Double-Gate FinFET

- L_{gate}=18 nm, w_{si}=11 nm
- Midgap metal gate (typically TiN)
- Gate-S/D doping underlap to control V_t and short channel effects
- Undoped body



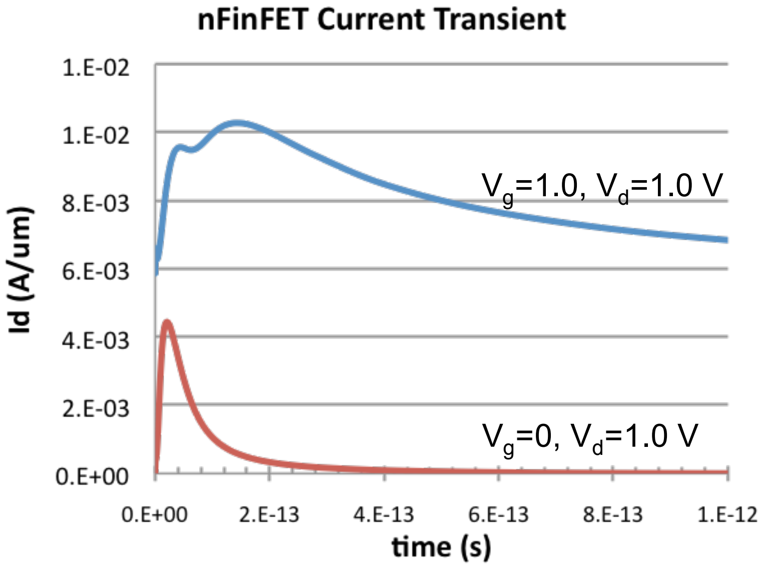
FinFET top cross-sectional view

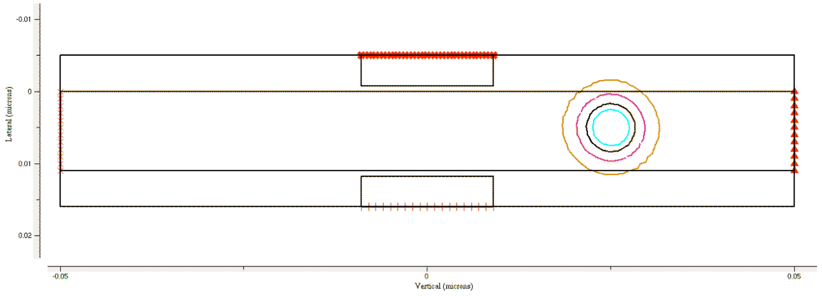


nFinFET I-V characteristic

Double-Gate FinFET

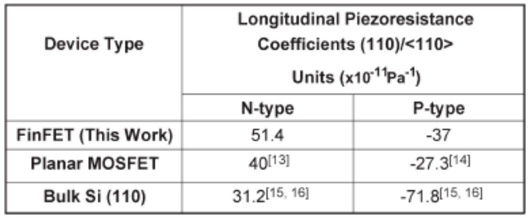
- nFinFET current transients



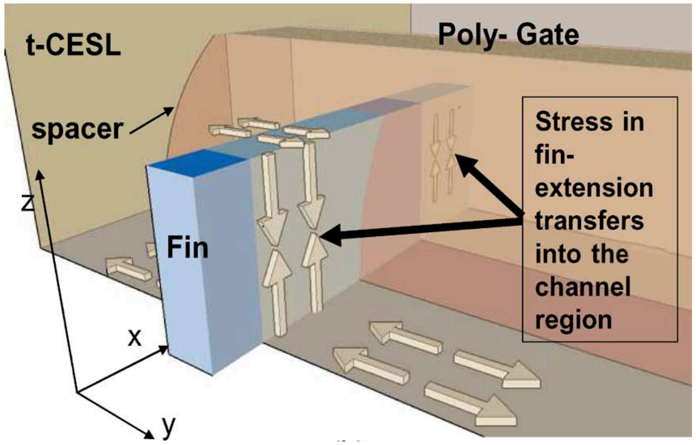


Apply piezoresistance model to
3-D strained FinFET

TABLE I
LONGITUDINAL PIEZORESISTANCE COEFFICIENTS FOR n- AND p-FINFETS ALONG WITH PREVIOUS PUBLISHED DATA FOR PLANAR MOSFETS AND BULK SI (110)



Device Type	Longitudinal Piezoresistance Coefficients (110)/<110> Units ($\times10^{-11}Pa^{-1}$)	
	N-type	P-type
FinFET (This Work)	51.4	-37
Planar MOSFET	40[13]	-27.3[14]
Bulk Si (110)	31.2[15, 16]	-71.8[15, 16]



Stress in fin-extension transfers into the channel region

Suthram S., *et al.* EDL 2008

Summary

- Work Toward Parallel Efficiency
  - Need to work on bricks, unrefinement
  - Element Based Assembly
- Added Physical Operators
  - Added Strain - 3D, parameterizable
  - Calibrate Effect from Device Measurements
- Begun Simulation of Advanced DG Structures