Physically-Based Analytic Model for Strain-Induced Mobility Enhancement of Holes

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Layout of Talk

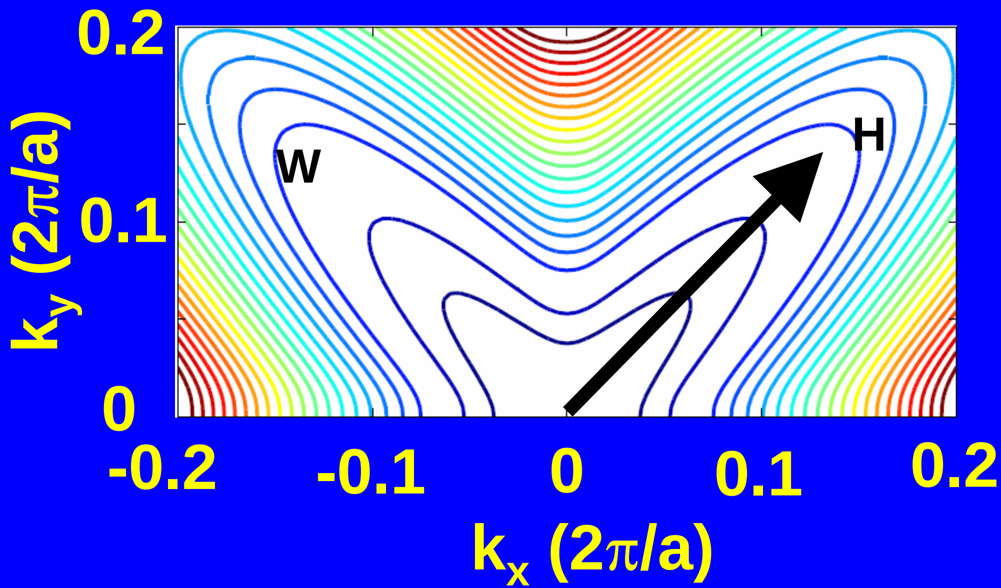
- Motivation
- Physics of Hole Mobility Enhancement
- Analytical Model
- Calibration and Results
- Conclusions

Motivation

- **Strain offers new possibilities for improved device performance by improving mobility**
- **Mobility enhancement induces no capacitance penalty**
- **Modeling essential for device optimization**
- **Empirical models often too awkward, difficult to capture many-parameter interactions**
- ***Need physically-based compact model***

Physics of Mobility Enhancement I

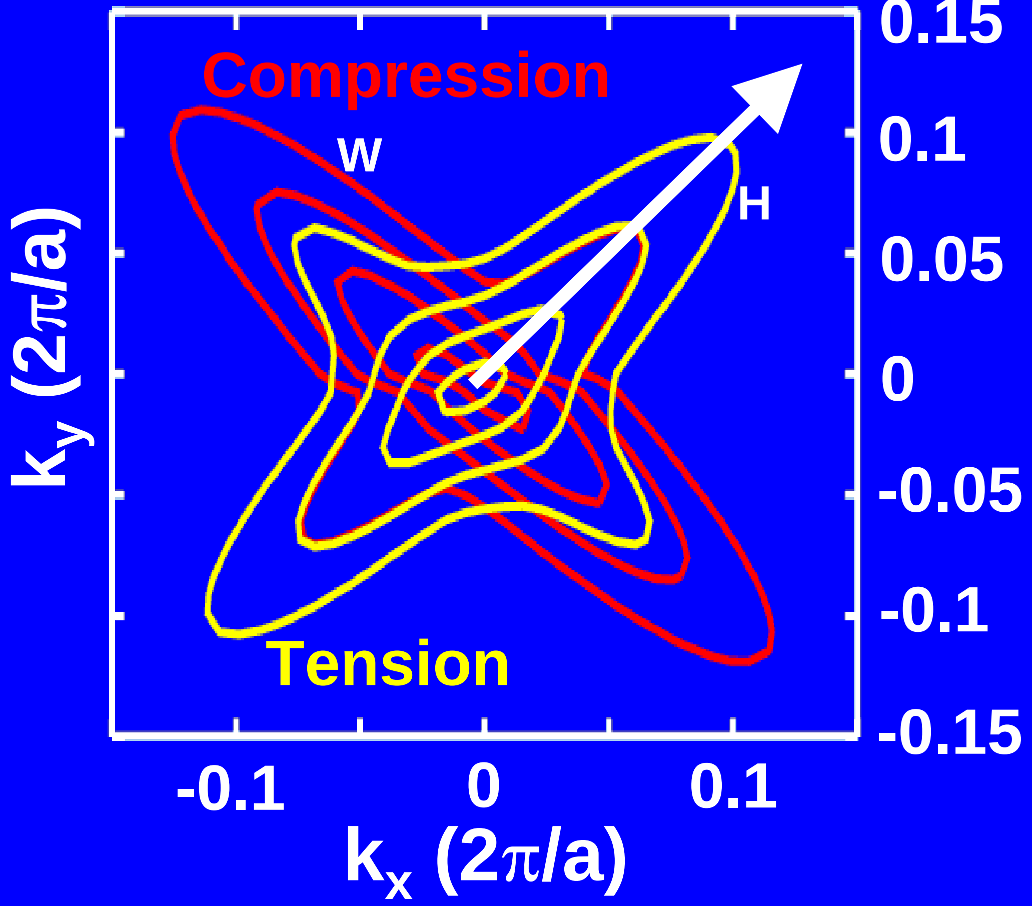
- Consider only heavy hole band



$$J = \iiint_k \frac{q^2\tau}{\eta^2}\frac{df_0}{dE}\underbrace{\nabla_k E\left(\nabla_k E \cdot \vec{F}\right)}_{\text{“effective mass”}} d^3k$$

- W regions have much lower mass than H regions

Physics of Mobility Enhancement II

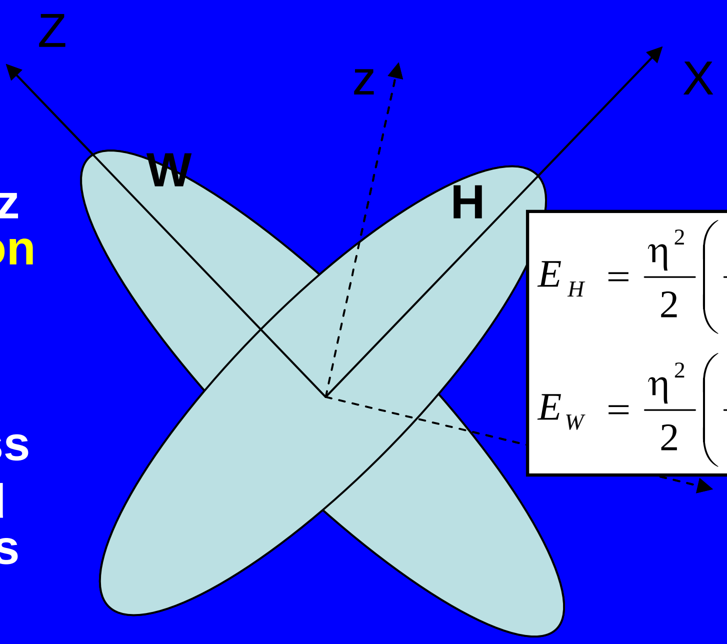


- Redistribution in k-space caused by stress
- Compressive stress lowers energy of W regions, tensile stress lowers energy of H regions
- Hole mobility improved under compression – reduced effective mass

Analytic Band Representation

- Create a very simple model to mimic the basic features:
  - Use heavy holes only - for stress regions of interest, hh are ~85% of overall population
  - Represent hh bands in xz plane using superposition of ellipsoids
  - Relative energy and curvatures of the bands modulated through stress
  - Relative populations and effective masses of holes modulated by stress

Lowercase: “transport” coordinates
Uppercase: Principal coordinates



$$E_H = \frac{\eta^2}{2}\left(\frac{k_X^{\ 2}}{m_{HX}} + \frac{k_Z^{\ 2}}{m_{HZ}}\right) + \frac{\Delta}{2}$$

$$E_W = \frac{\eta^2}{2}\left(\frac{k_X^{\ 2}}{m_{WX}} + \frac{k_Z^{\ 2}}{m_{WZ}}\right) - \frac{\Delta}{2}$$

Model Details - Mobility

- Obtain expression for mobility component along field direction

$$\bar{\mu}_P = \begin{pmatrix} \frac{\langle\tau\rangle f_1}{m_{t1}} + \frac{\langle\tau\rangle f_2}{m_{l2}} & 0 \\ 0 & \frac{\langle\tau\rangle f_1}{m_{l1}} + \frac{\langle\tau\rangle f_2}{m_{t2}} \end{pmatrix}, \ \bar{\mu} = R\bar{\mu}_P R^T. \ (1)$$

$$\mu \equiv \mu_{xx} = 2\mu_0 \frac{m_t m_l}{m_t + m_l}\left[\cos^2\theta\left(\frac{f_1}{m_{t1}} + \frac{f_2}{m_{l2}}\right) + \sin^2\theta\left(\frac{f_1}{m_{l1}} + \frac{f_2}{m_{t2}}\right)\right]. \quad (2)$$

- Use MB statistics to approximate relative populations, Δ is energy separation of ellipsoids

$$f_1 = \frac{\exp\left(\frac{\Delta}{2kT}\right)}{\exp\left(\frac{\Delta}{2kT}\right) + \exp\left(-\frac{\Delta}{2kT}\right)} = \frac{1}{1 + \exp\left(-\frac{\Delta}{kT}\right)}, f_2 = 1 - f_1, \ (3)$$

Model Details – Stress

- Express given stress in crystal coordinates, separate into **shear, biaxial, and asymmetric components**

$$S = \begin{pmatrix} b+a & s \\ s & b-a \end{pmatrix}$$

- Typical Case: Sxx and Szz stress in [110] and perpendicular direction

$$S = \frac{1}{2}\begin{pmatrix} s_{xx}+s_{zz} & s_{xx}-s_{zz} \\ s_{xx}-s_{zz} & s_{xx}+s_{zz} \end{pmatrix}$$

- Express bandstructure related parameters as expansions of shear, biaxial stress

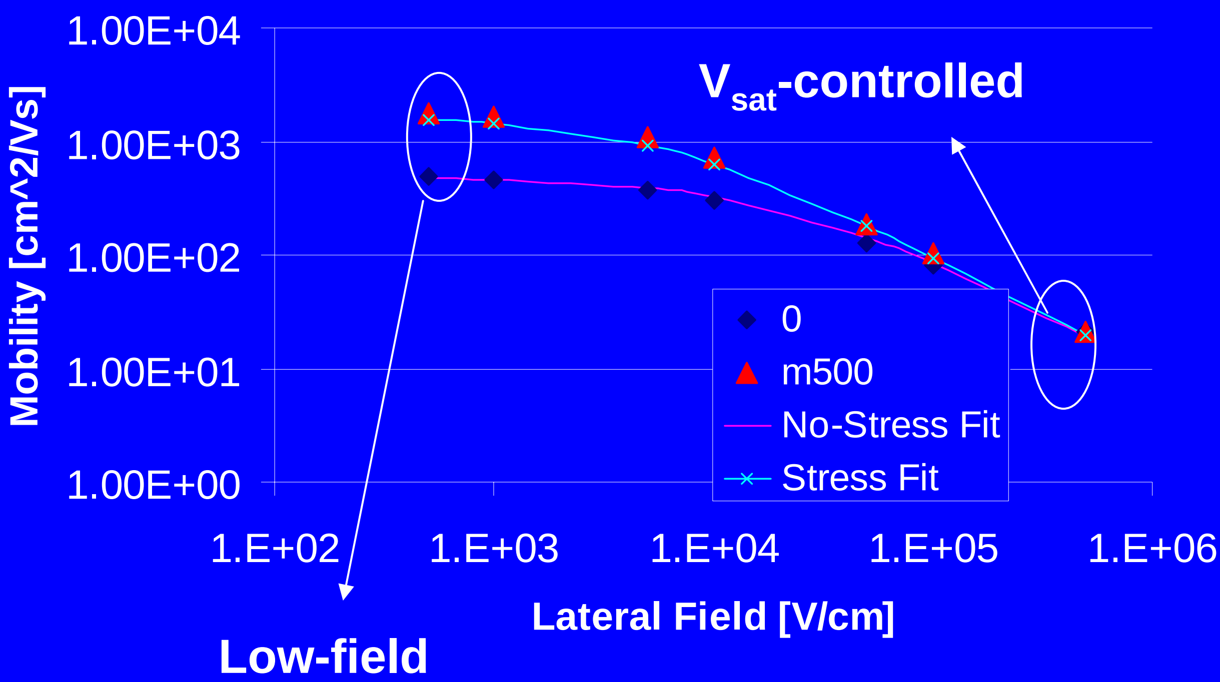
$$\Delta = \sum_i d_i s^i$$

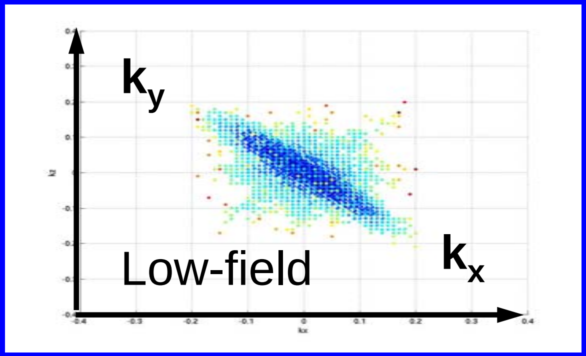
$$\frac{1}{m_{ti}} = \frac{1}{m_{ti0}}\left[1+\sum_i ms_i s^i + \sum_i mb_i b^i\right]$$

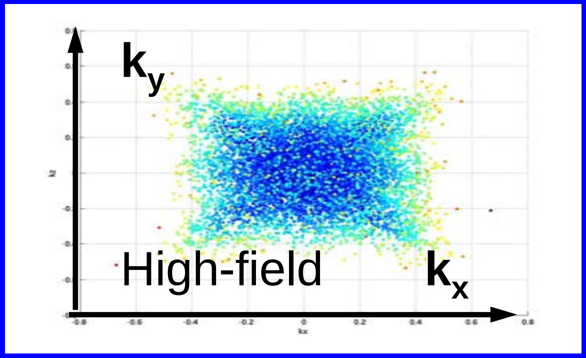
- **Only important parameters:**
  - d_1, mb_2

High-Field Behavior and Model

Mobility Saturation Behavior

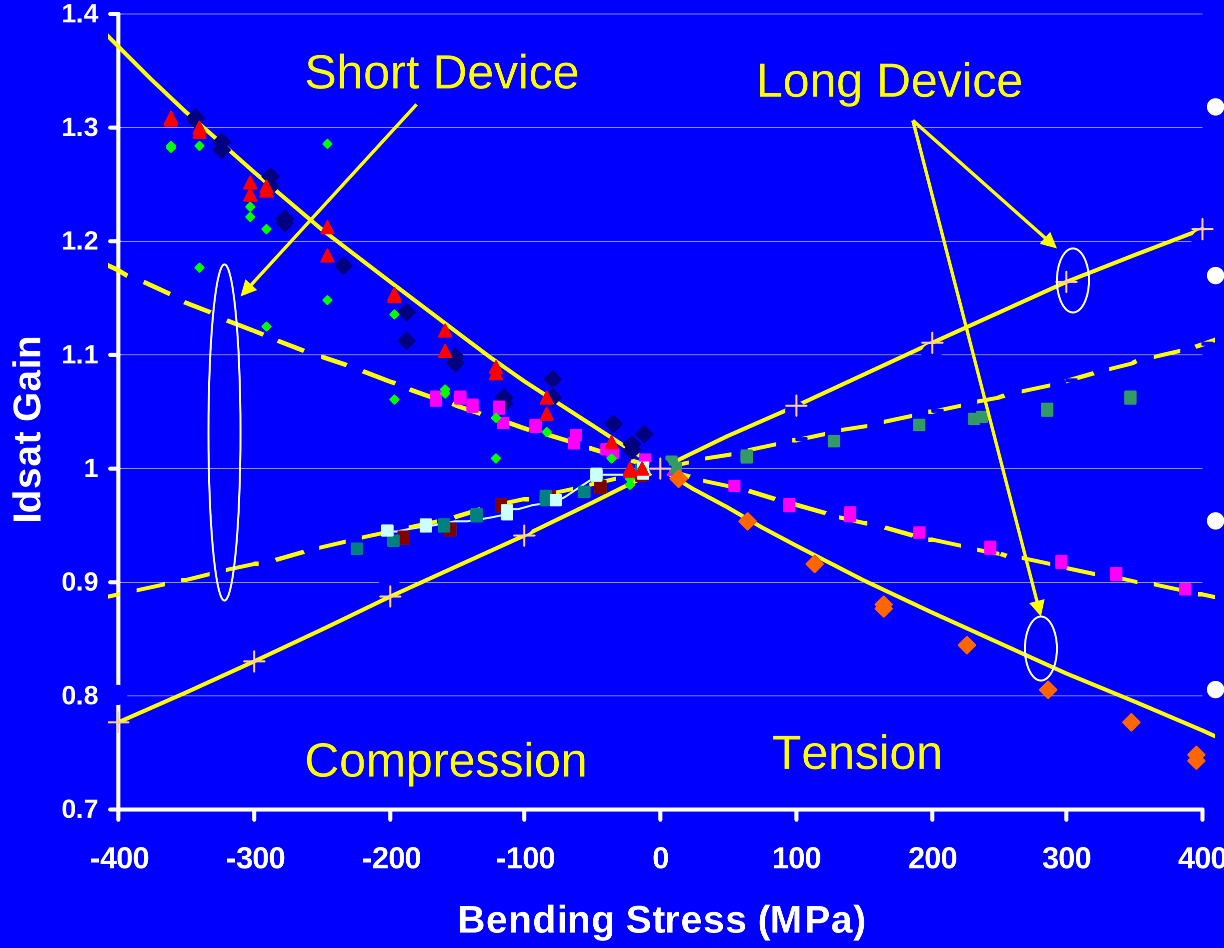






- **High energy carriers tend to symmetrize population**
- **Modeled through temperature term** $kT = kT_L + eE < s >$

Model Calibration and Results



- Calibration to wafer-bending data
- Long (2mm) and short (65 nm) devices
- Two channel orientations
- Compressive and tensile bending

Conclusions

- Presented analytic model for strain-induced mobility enhancement for holes in (100) Si
- Model captures mobility behavior as a function of arbitrary in-plane stress, electric field, channel orientation, and temperature
- Model calibration extends from 400 MPa tensile to 700 MPa compressive