ROCHESTER INSTITUTE OF TECHNOLOGY
MICROELECTRONIC ENGINEERING

Piezoresistance in Silicon

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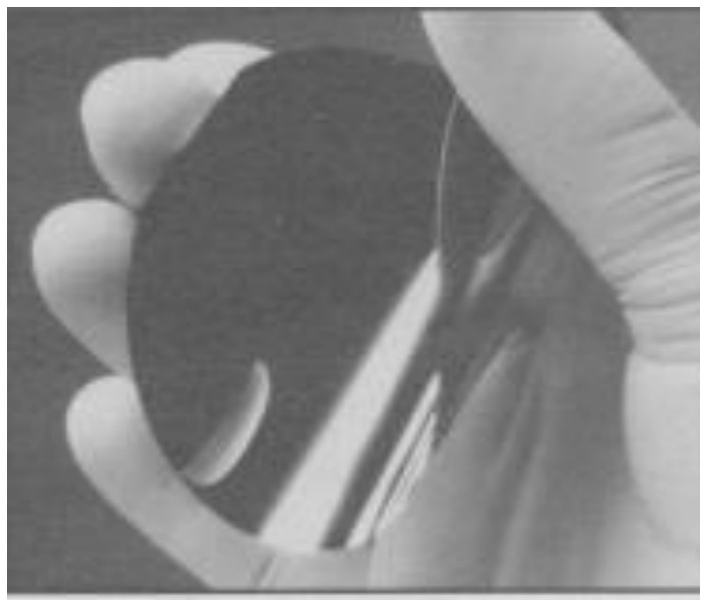
INTRODUCTION

The piezoresistive effect was first reported in 1954 [1] and has been used in making sensors for years. The effect of strain on the mobility of electrons and holes in semiconductors is important in today's sensors and transistors.



Thickness = 10 µm
Diameter 75 mm

STRAINED SILICON

A simple way to think about strained silicon follows: Tensile strain causes the silicon atoms to be pulled further apart making it easier for electrons to move through the silicon. On the other hand moving the atoms further apart makes it harder for holes to move because holes require bound electrons to move from a silicon atom to a neighboring silicon atom in the opposite direction, which is more difficult if they are further apart. Thus tensile strain increases mobility in n-type silicon and compressive strain increases mobility in p-type silicon (devices).

Strain can be created globally or locally. Growing an epitaxial layer of silicon on a silicon/germanium substrate creates (global) biaxial tensile strain in the silicon. N-MOSFETS built on these wafers will have higher mobility. P-MOSFETS will have lower mobility. Local strain can be created for each transistor such that N-MOSFETS see tensile strain and P-MOSFETS see compressive strain improving both transistors mobility. Local strain techniques include capping layers and introducing Ge or C in the source/drain regions.

CHARLES SMITH 1954

PHYSICAL REVIEW VOLUME 94, NUMBER 1 APRIL 1, 1954

Piezoresistance Effect in Germanium and Silicon

CHARLES S. SMITH
Bell Telephone Laboratories, Murray Hill, New Jersey
(Received December 30, 1953)

Uniaxial tension causes a change of resistivity in silicon and germanium of both *n* and *p* types. The complete tensor piezoresistance has been determined experimentally for these materials and expressed in terms of the pressure coefficient of resistivity and two simple shear coefficients. One of the shear coefficients for each of the materials is exceptionally large and cannot be explained in terms of previously known mechanisms. A possible microscopic mechanism proposed by C. Herring which could account for one large shear constant is discussed. This so called electron transfer effect arises in the structure of the energy bands of these semiconductors, and piezoresistance may therefore give important direct experimental information about this structure.

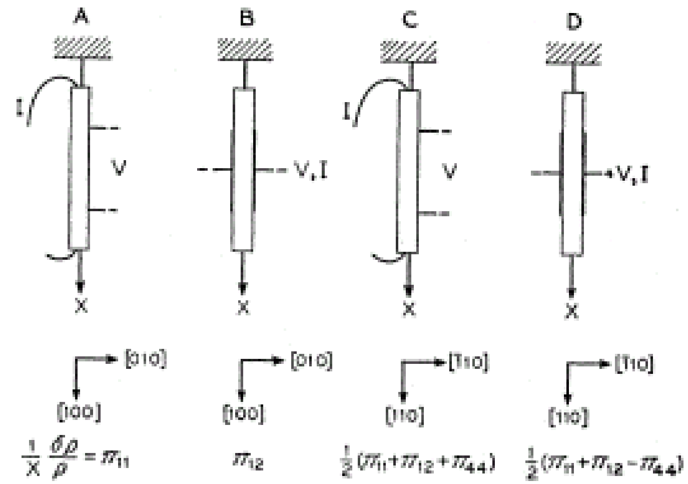
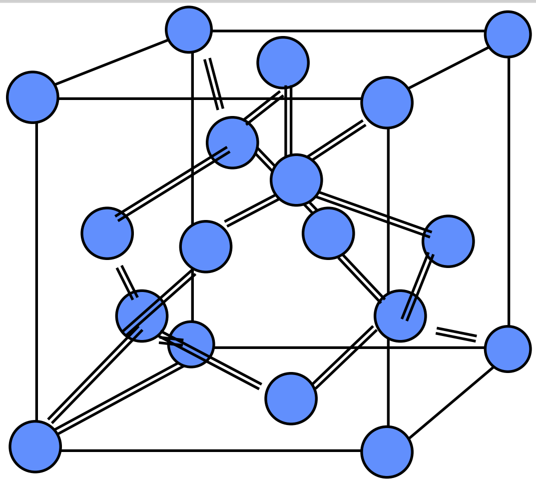


FIG. 1. Schematic diagram showing the stress system, the crystallographic orientations and the electrode structures which have been used. Arrangements A and C are designated as longitudinal in the text; B and D are called transverse.

CRYSTAL STRUCTURE

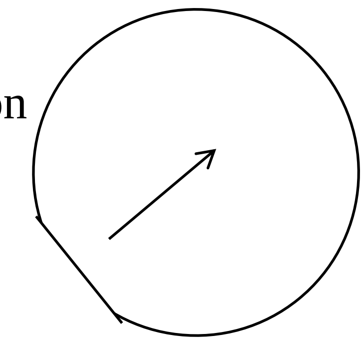
Diamond Lattice (Silicon)



Si

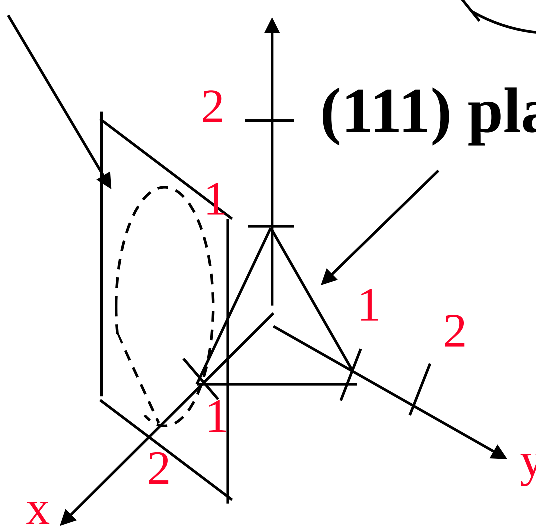
Equivalent Planes (100), (010), etc.
Directions <110>, <011>, etc.

(100) wafer
<110> direction



(100) plane

(111) plane



Miller Indices
(1/x,1,y,1/z)
smallest integer set

PIEZORESISTANCE

Piezoresistance is defined as the change in electrical resistance of a solid when subjected to stress. The piezorestivity coefficient is Π and a typical value may be 1E^{-10} cm^2/dyne.

The fractional change in resistance ΔR/R is given by:

$$\Delta R/R = \Pi\, \sigma$$

where σ is the stress in dyne/cm^2.

10 dyne/cm^2 = 1Pa = 1 newton/m^2

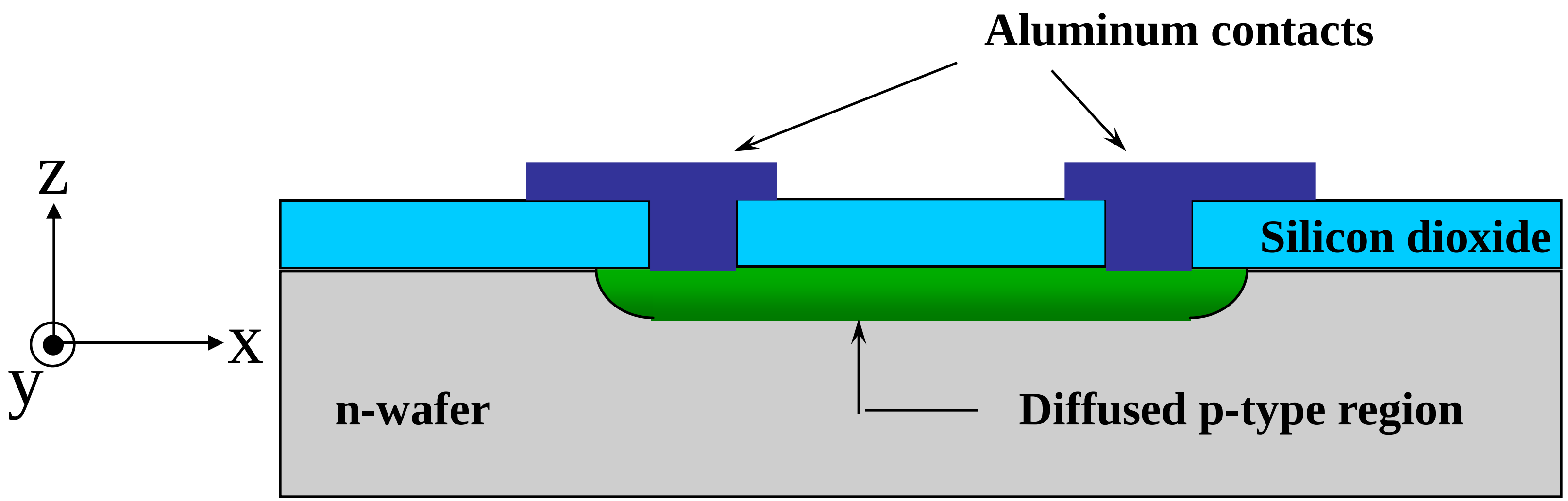
Hooks Law:

$$\sigma = E\, \varepsilon$$

where

E is Young's modulus

SINGLE CRYSTAL DIFFUSED RESISTORS



The n-type wafer is always biased positive with respect to the p-type diffused region. This ensures that the pn junction that is formed is in reverse bias, and there is no current leaking to the substrate. Current will flow through the diffused resistor from one contact to the other. The I-V characteristic follows Ohm's Law: I = V/R

Sheet Resistance $= \rho_s \sim 1/(\,q\mu\ \mathrm{Dose})$ ohms/square

$R = L/W \quad 1/(q\mu\ \mathrm{Dose})$

EXPRESSION FOR RESISTANCE

$$R = Ro\,[\,1 + \pi_L \sigma_{xx} + \pi_T(\sigma_{yy} + \sigma_{zz})]$$

$$Ro = (L/W)(1/(q\mu(N,T)\ Dose))$$

π_L is longitudinal piezoresistive coefficient

π_T is transverse piezoresistive coefficient

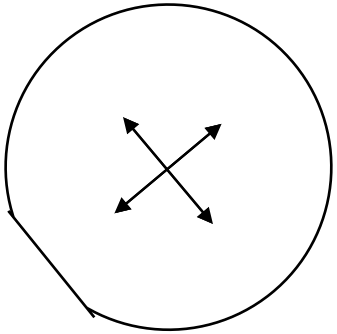
σ_{xx} is the x directed stress

σ_{yy} is the y directed stress

σ_{zz} is the z directed stress

PIEZORESISTANCE COEFFICIENTS

(100) wafer
<110> directions

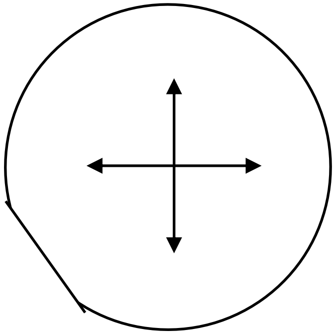


In the <110> direction

	π_L (E^{-11}/Pa)	π_T (E^{-11}/Pa)
Electrons	**-31.6**	**-17.6**
holes	**71.8**	**-66.3**

Direction of Carrier Flow

(100) wafer
<100> directions

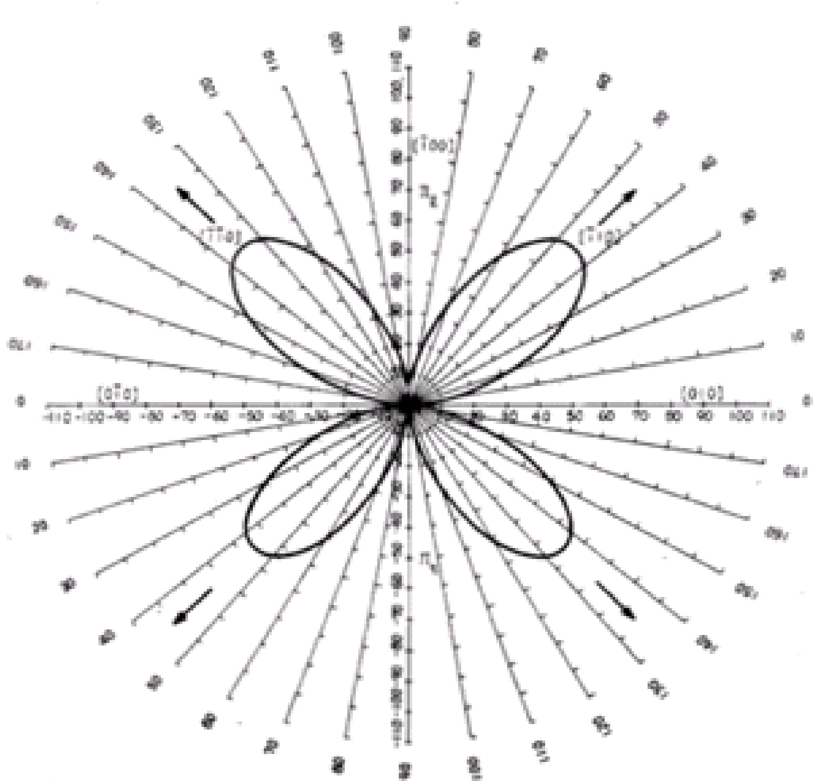


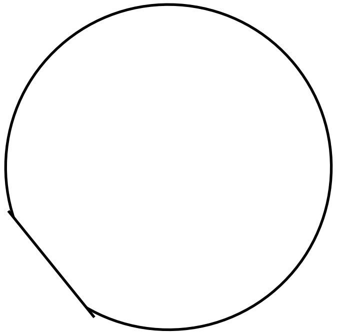
In the <100> direction

	π_L (E^{-11}/Pa)	π_T (E^{-11}/Pa)
Electrons	**-102**	**53.4**
holes	**6.6**	**-1.1**

Tensile strain in (100) silicon increases mobility for electrons for flow in <110> direction
Compressive strain in (100) silicon increases mobility for holes for flow in <110> direction

PIEZORESISTANCE COEFFICIENTS VS DIRECTION





- Piezoresistance coefficients at room temperature for the (001) plane of p-Si

[2]

PIEZORESISTANCE COEFFICIENTS VS DIRECTION

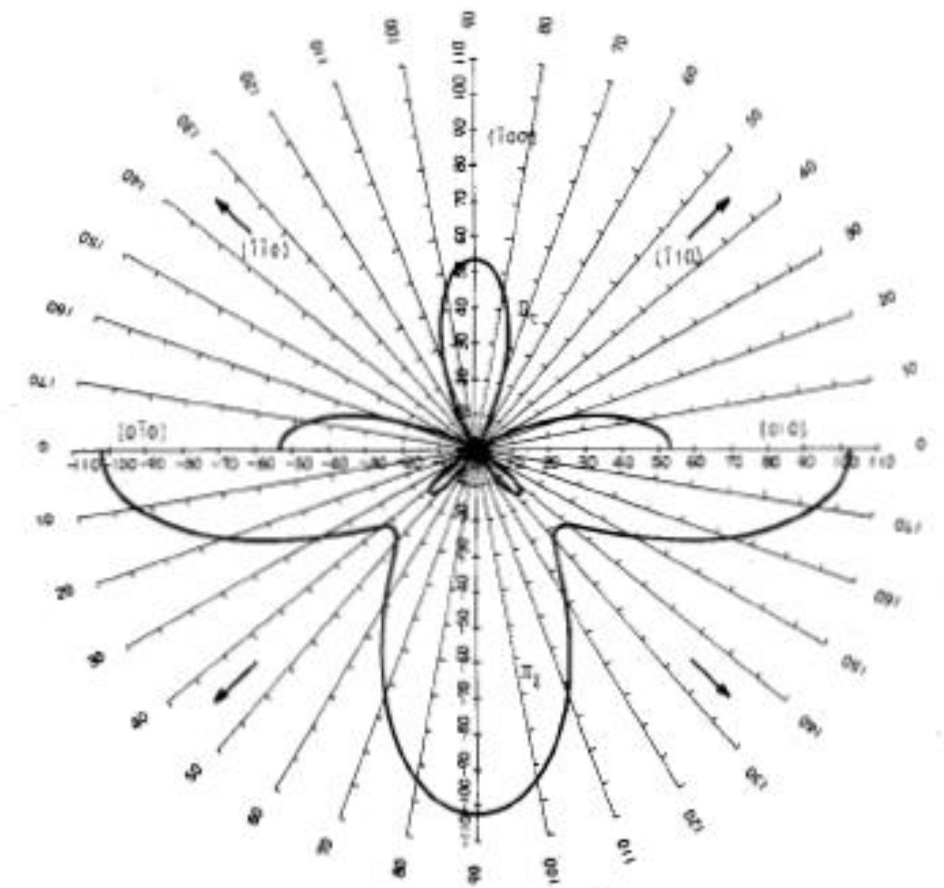
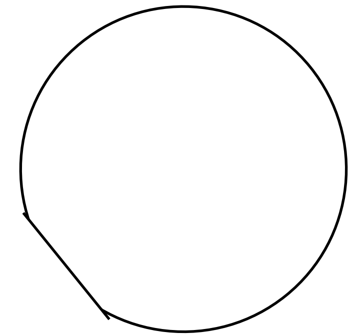


Fig. 2. Room temperature piezoresistance coefficients in the (001) plane of n-Si (10^{-12} cm^2/dyne).



EXAMPLE: PIEZORESISTANCE

Example: Find the maximum stress in a simple polysilicon cantilever with the following parameters. Ymax = 1 µm, b=4 µm, h=2µm, L=100 µm

$\sigma_{x=0}$ = 5.6e7 newton/m2 = 5.6e8 dyne/cm2

From example in mem_mech.ppt

Continue Example: What is the change in resistance given Π = 71.8e-10 cm^2/dyne

Δ R/R = Π σ = (71.8e-10 cm2/dyne)(5.6e8 dyne/cm2)
= 4.02%

10 dyne/cm^2 = 1 Pa = 1 newton/m^2

SUMMARY FOR MOBILITY / STRAIN

1. Mobility is affected by strain in semiconductors. Mobility can be increased or decreased depending on the type of strain (tensile, compressive) and the direction of strain relative to crystal orientation and current flow.

For (100) wafers and current flow in <110> direction:

2. Tensile strain n-type silicon enhances mobility of electrons. Tensile strain transverse to current flow enhances mobility of electrons.

3. Compressive strain in the direction of current flow in p-type silicon enhances mobility of holes. Tensile strain transverse to current flow enhances mobility of holes.

REFERENCES

1. Charles S. Smith, “Piezoresistance Effect in Germanium and Silicon,” Physical Review, Vol 94, No.1, April 1, 1954.
2. Y. Kanda, “A graphical representation of the piezoresistance coefficients in silicon,” *Electron Devices, IEEE Transactions on*, vol. 29, no. 1, pp. 64-70, 1982.
3. C. Mazure, and I. Cayrefourcq, "Status of device mobility enhancement through strained silicon engineering." pp. 1-6.
4. A. A. Barlian, W. T. Park, J. R. Mallon *et al.*, “Review: Semiconductor Piezoresistance for Microsystems,” *Proceedings of the IEEE*, vol. 97, no. 3, pp. 513-552, 2009.

HOMEWORK - PIEZORESISTANCE

1. If a p-type diffused resistor on a simple cantilever experiences a tensile stress of 50 MPa what will the % change in resistance be if the resistor is oriented with its length in the same direction as the strain?
2. If a p-type diffused resistor on a simple cantilever experiences a tensile stress of 50 MPa what will the % change in resistance be if the resistor is oriented with its width in the same direction as the strain?