Possibilities for LWIR Detectors using MBE-grown Si/(Si$_{1-x}$Ge$_x$) Structures

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Traditionally, LWIR detection in Si-based structures has involved either extrinsic Si or Si/metal Schottky barrier devices. Molecular beam epitaxially (MBE) grown Si and Si/Si$_{1-x}$Ge$_x$ heterostructures offer new possibilities for LWIR detection, including sensors based on intersubband transitions as well as improved conventional devices. The improvement in doping profile control of MBE in comparison with conventional chemical vapor deposited (CVD) Si films has resulted in the successful growth of extrinsic Si:Ga, blocked impurity-band conduction detectors. These structures exhibit a highly abrupt step change in dopant profile between detecting and blocking layers which is extremely difficult or impossible to achieve through conventional epitaxial growth techniques. Through alloying Si with Ge, Schottky barrier infrared detectors are possible, with barrier height values between those involving pure Si or Ge semiconducting materials alone. For both n-type and p-type structures, strain effects can split the band edges, thereby splitting the Schottky threshold and altering the spectral response. Our measurements of photoresponse of n-type Au/Si$_{1-x}$Ge$_x$ Schottky barriers demonstrate this effect. For intersubband multiquantum well (MQW) LWIR detection, Si$_{1-x}$Ge$_x$/Si detectors grown on Si substrates promise comparable absorption coefficients to that of the Ga(Al)As system while in addition offering the fundamental advantage of response to normally incident light as well as the practical advantage of Si-compatibility. We have grown Si$_{1-x}$Ge$_x$/Si MQW structures aimed at sensitivity to IR in the 8 to 12 μm region and longer, guided by recent theoretical work. Preliminary measurements of our n- and p-type Si$_{1-x}$Ge$_x$/Si MQW structures will be presented.

POSSIBILITIES FOR LWIR DETECTORS USING MBE-GROWN Si(/SiGe) STRUCTURES

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HUGHES RESEARCH LABORATORIES

OUTLINE

• INTRODUCTION

• EXTRINSIC Si DETECTORS

• Si$_{1-x}$Ge$_x$/Si MQW DETECTORS

• SCHOTTKY BARRIERS ON Si$_{1-x}$Ge$_x$

• SUMMARY
TRADITIONAL MID TO LONG WAVELENGTH IR DETECTORS IN Si

• EXTRINSIC DETECTORS
  – PC TYPE
  – BLOCKED IBC TYPE

• SCHOTTKY DETECTORS
  – e.g., PtSi/Si

MATERIALS PRODUCED BY Si MBE

- MANY EPITAXIAL COMBINATIONS POSSIBLE
  - $\text{Si}_{1-x}\text{Ge}_x$ (COHERENTLY STRAINED)
  - SILICIDES ($\text{M}_x\text{Si}_y$)
  - SELECTIVELY DOPED Si
  - OTHER
EXTRINSIC Si DETECTORS

- MBE $\Rightarrow$ SUPERIOR DOPANT PROFILE CONTROL FOR FAST DIFFUSERS (e.g., Ga IN Si)

CONCENTRATIONS > SOLID SOLUBILITY SOMETIMES POSSIBLE

- MBE + LOW-ENERGY ION IMPLANT PROVIDES GREAT FLEXIBILITY

\[ \begin{array}{|c|c|}
\hline
\text{thk (\text{\textmu}m)} & \text{\(N_{Ga} (\text{cm}^{-3})\)} \\
\hline
2.0 & \sim 1 \times 10^{16} \\
5.0 \text{ TO } 12.0 & \sim 1 \times 10^{18} \\
\hline
\end{array} \]
STARTING BURIED CONTACT
LAYER THICKNESS

SURFACE CONTACT

DESIRED PROFILE

DETECTING LAYER

BLOCKING LAYER

CARRIER CONCENTRATION, cm⁻³

DEPTH, µm

HAB 0.33

EPI

SUBSTRATE

INPUT

PHOTONS
MBE Si:Ga BLOCKED IBC RESULTS

- IBC BEHAVIOR DEMONSTRATED

- WAVELENGTH RESPONSE GOOD (~ 12 \( \mu \)m PEAK)
  HOWEVER: POOR Q.E. DUE TO
  - LIMITED PURITY (NEED ~ \( 10^{12} \) CM \(^{-3}\))
  - TOO MANY PARTICULATES

HRL IS DEVELOPING A GAS-SOURCE Si MBE TECHNIQUE TO IMPROVE UPON ABOVE RESULTS
SiGe/Si MULTI–QUANTUM WELL DETECTOR

- Tunable response throughout infrared
- Normal–incidence absorption
- Predicted absorption stronger than GaAs–based

SiGe/Si MQWS – IMPORTANT ISSUES

- STRAIN
  - CRITICAL THICKNESS(ES)
  - EFFECT ON BAND STRUCTURE

- COND. BAND ANISOTROPY

- GROWTH ISSUES
  - GOOD "RELAXED" LAYER
  - n-TYPE DOPING
  - UNIFORMITY OF THIN LAYERS
\[ \text{Si}_{1-x}\text{Ge}_x \text{ ON Si} \]

- **KEY FEATURE**
  - LATTICE CONSTANT MISMATCH
    (~ 4.2% Ge TO Si)

- **EPITAXIAL POSSIBILITIES**
  - COHERENTLY STRAINED GROWTH
  - UNSTRAINED (RELAXED) GROWTH

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**STRAINED**

**UNSTRAINED**

---

**SINGLE FILM CRITICAL THICKNESS**

(Si parameters)

- Van der Merwe, 1963
- Matthews & Blakeslee*, 1974
- People & Bean, 1986

* TH. EQ.
**Si(Ge) BAND STRUCTURE**

**EFFECT OF STRAIN ON Si$_{1-x}$Ge$_x$ BAND STRUCTURE**

Si$_{1-x}$Ge$_x$ ON Si (100):

Si$_{1-x}$Ge$_x$ ON Si$_{0.5}$Ge$_{0.5}$ (100):
USEFUL GROWTH RANGE

2-Fold Conduction Band Offset (eV)
(Lattice Matched to Substrate)

Ge Concentration in Epilayer

500°C 350°C

STRAINED ON (5000Å SL)

Free-Standing

HRXRD - SiGe/Si MQW

Filename: h16 Sample: HA90.016 HRXRD (004)

L = 200Å

\( t_{Si} = 170Å \) \( t_{Ge_xSi_{1-x}} = 30Å \) \( X = 53\% \)
SYNOPSIS - SiGe/Si MQW'S - (100) FILMS

<table>
<thead>
<tr>
<th>WELL</th>
<th>BARRIER</th>
<th>BUFFER</th>
<th>NON-PARAB.</th>
<th>MBE GROWTH</th>
</tr>
</thead>
<tbody>
<tr>
<td>n-Type</td>
<td>Si</td>
<td>Si_{1-x} Ge_x</td>
<td>Si_{1-x} Ge_x(RLX)</td>
<td>WEAK</td>
</tr>
<tr>
<td>p-Type</td>
<td>Si_{1-x} Ge_x</td>
<td>Si</td>
<td>Si(COH)</td>
<td>STRONG</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>DETECTS NORM. ALUM.?</th>
<th>8 - 12mm?</th>
<th>$\alpha$ (RAIC(CM$^{-1}$))</th>
</tr>
</thead>
<tbody>
<tr>
<td>n-(100)</td>
<td>NO</td>
<td>YES</td>
</tr>
<tr>
<td>n-(110)</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>n-(111)</td>
<td>YES</td>
<td>NO</td>
</tr>
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</table>
SCHOTTKY BARRIERS ON Si AND Ge
FOR SELECTED METALS (300K)

<table>
<thead>
<tr>
<th></th>
<th>Ag</th>
<th>Al</th>
<th>Au</th>
<th>Cu</th>
<th>Ni</th>
<th>Pt</th>
<th>W</th>
</tr>
</thead>
<tbody>
<tr>
<td>(n) Si</td>
<td>0.78</td>
<td>0.72</td>
<td>0.80</td>
<td>0.58</td>
<td>0.61</td>
<td>0.90</td>
<td>0.67</td>
</tr>
<tr>
<td>(p) Si</td>
<td>0.54</td>
<td>0.58</td>
<td>0.34</td>
<td>0.46</td>
<td>0.51</td>
<td></td>
<td>0.45</td>
</tr>
<tr>
<td>(n) Ge</td>
<td>0.54</td>
<td>0.48</td>
<td>0.59</td>
<td>0.52</td>
<td>0.49</td>
<td></td>
<td>0.48</td>
</tr>
<tr>
<td>(p) Ge</td>
<td>0.50</td>
<td></td>
<td>0.30</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$\Delta Q_n \gg \Delta Q_p$ IN MOST CASES

$\Rightarrow E_F^{\text{METAL}} \approx \text{PINNED TO VALENCE BAND EDGE}$

INTERPOLATE VALUES FOR UNSTRAINED $\text{Si}_{1-x} \text{Ge}_x$?

FROM S.M. SZE, "PHYSICS OF SEMICONDUCTOR DEVICES," WILEY, 1981, CHAP. 5

FOWLER PLOT (T = 300K)

$\sqrt{PR/\text{PHOTON}}$

ENERGY, meV

335
FOWLER PLOT  
(T = 300K)

COHERENTLY STRAINED  \( n - Si_{0.77}Ge_{0.23}/Au \) SCHOTTKY

TWO-BARRIER FIT:

\[ Q_{HI} = 0.953 \text{ eV} \quad (93\%) \]
\[ Q_{LO} = 0.775 \text{ eV} \quad (7\%) \]
SUMMARY

• Si MBE ⇒ MULTILAYERS IN A Si-PROCESS - COMPATIBLE TECHNOLOGY

• BETTER "CONVENTIONAL" DEVICES POSSIBLE (E.G., Si:Ga IBC)

• NOVEL DEVICES POSSIBLE (MQW)

• SiGe/Si MQW ADVANTAGE: DETECTS NORMALLY INCIDENT LIGHT

• Si(Ge) STRAINED SCHOTTKY BARRIERS: INTERESTING PROSPECTS FOR DEVICES AND PHYSICS