GERMANIUM BLOCKED IMPURITY BAND (BIB) DETECTORS

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1. INTRODUCTION

- Extrinsic, photoconductive semiconductor detectors cover the infrared spectrum from a few \( \mu m \) up to 250 \( \mu m \).

- Photoconductors exhibit high responsivity and low noise equivalent power.

- The Si blocked impurity band (BIB) detector invented by M. D. Petroff and M. G. Stapelbroek has a number of advantages over standard bulk photoconductors. These include:
  - smaller detection volume leading to a reduction of cosmic ray interference
  - extended wavelength response because of dopant wavefunction overlap
  - photoconductive gain of unity
2. **Ge BIB**

- The success of Si BIB detectors has been a strong incentive for the development of Ge BIB detectors.

- The advantages of Si BIB detectors stated above should, in principle, be realizable for Ge BIB detectors.

- If Ge BIB detectors can be made to work out to 250 μm with high responsivity and sufficiently low dark current, they could replace stressed Ge:Ga photoconductors.

- Can the dark current be reduced to acceptable levels?
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[110x511]Contact, I
[351x587]41 - Doped infrared-active material, ~1mm thick.

Figure 1(a). Schematic of conventional detector.

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Pure epilayer, ~ 5 \(\mu\)m thick.

Doped infrared-active substrate, ~ 50 \(\mu\)m thick.

Ge:Ga \(2 \times 10^{16}\) cm\(^{-3}\)

Figure 1(b). Schematic of BIB detector.
Figure 2(a). Doping levels in a conventional Ge detector.

Figure 2 (b). Doping levels in a Ge BIB detector.
Fig. 3. Schematics of space charge, electric field and potential energy for a reverse biased p-type BIB detector.
3. **Ge BIB DETECTOR DEVELOPMENT**

3.1. Epitaxial Blocking Layer Devices

3.1.1. Ge epitaxy

- Whereas Si epitaxy techniques have been developed to a very high degree of perfection, Ge epitaxy has been attempted only on a few occasions.

- Ge chemistry is very different from Si chemistry.

- Ultra-pure Ge compounds \([\text{Ge(CH}_3\text{)}_4, \text{Ge(C}_2\text{H}_5\text{)}_4]\) are being developed for III-V semiconductor technology. They may be useful to Ge epitaxy.
Substrate choice and preparation

- We have used a number of different crystals with various crystallographic orientations in the development of Ge epitaxy:
  - n-type wafers (~$10^{11}$ cm$^{-3}$) are used for the electrical characterization of the epitaxial layers which are typically p-type because of residual copper contamination (junction isolation).
  - p-type wafers (~$10^{15}$ cm$^{-3}$) are used for I-V comparison tests with conventional photoconductors.
  - p-type wafers (~$2 \times 10^{16}$ cm$^{-3}$, low compensation) are used for Ge BIB detectors.
• Wafer polishing process:
  - mechanical planar lapping with alumina slurry.
  - mechano-chemical polishing with syton containing $\text{H}_2\text{O}_2$.
  - brief etch in HNO$_3$:HF (3:1) followed by soak in HF (1% in H$_2$O) to remove oxides.

• Epitaxy:
  - first experiments with atmospheric pressure vapor phase epitaxy (VPE). Disadvantage: high substrate temperature, $\text{H}_2$ diluted feed gas (contamination, diffusion of dopants into the blocking layer).
  - current experiments are performed with low pressure VPE. Advantage: low substrate temperature.
Fig. 4. Schematic of horizontal VPE apparatus. Quartz tube is 5.7 cm O.D. x 75 cm long.
3.1.2. Characterization of epi layers

- Optical micrographs

- Variable temperature Hall effect and resistivity

- Rutherford backscattering (channeling) spectrometry (RBS)

- Secondary ion spectrometry (SIMS)

- Spreading resistance measurements
(100) $N_D - N_A = 1 \times 10^{14} / \text{cm}^3$
$580^\circ\text{C}; \ 5 \text{sccm GeH}_4,$
with H$_2$ reduction step,
polycrystalline deposition

(113) $N_D - N_A = 2 \times 10^{14} / \text{cm}^3$
$580^\circ\text{C}; \ 5 \text{sccm GeH}_4,$
with H$_2$ reduction step,
no growth (etching)

(113) $N_D - N_A = 5 \times 10^{11} / \text{cm}^3$
$550^\circ\text{C}; \ 10\text{sccm GeH}_4,$
no H$_2$ reduction step,
single crystal deposition

Fig. 6. Optical micrographs of Ge epi layers.
Fig. 7. Variable temperature Hall effect measurements of a Ge epilayer on an n-type [113] substrate. The hole freeze-out curves indicate a light copper contamination. The two curves (+, *) are measurements of the same sample and demonstrate reproducibility.
Fig. 8. RBS channeling spectra of a Ge epi film (#636). The "cloudy" region shows significant dechanneling indicating a high defect concentration.
Fig. 9. SIMS of LPVPE Epi Films: Oxygen Concentration
Fig. 10. SIMS of LPVPE Epi Films: Carbon Concentration
3.1.3. Preliminary detector test results

- Responsivity

- Dark current
Fig. 11. Spreading resistance as a function of depth from the epilayer surface for: (a) an area of epilayer close to the leading edge of the wafer in II-16 where the growth rate was $\sim 0.06 \mu\text{mmin}^{-1}$, and (b) an area of epilayer farthest from the leading edge of the same wafer where the growth rate was $\sim 0.02 \mu\text{mmin}^{-1}$. The slight rise in resistivity at the very surface is due to the native oxide.
Fig. 12. Responsivity as a function of bias for detectors 13-2 and 13-3 at 2.3 K under reverse bias. The substrate material is moderately doped ($5 \times 10^{15}$ cm$^{-3}$). Such material exhibits hopping conduction but does not have extended wavelength spectral response. Tests were performed with a narrow band filter at $\lambda = 98.9$ $\mu$m.
Fig. 13. Dark current as a function of detector bias for detector 13-2 with an epilayer and for the same "detector" without an epilayer at 2.3 K under reverse bias. Below a bias of \( \sim 100 \text{ mV} \), the blocking layer effectively reduces hopping conduction in this moderately doped material \( (N_A - N_D = 5 \times 10^{15} \text{ cm}^{-3}) \).
Fig. 14. Dark current as a function of bias for detectors 13-2 and 13-3 at 2.3 K under reverse bias.
3.2. Ion Implied BIB Detectors

- Concept:
  - In case pure and structurally perfect epitaxial layers are hard to produce, we can resort to implantation of dopants into an ultra-pure crystal.

- Low energy B⁺-implantation tests:
  - three B⁺ energies: 150 keV, 95 keV, 50 keV form a 0.4 μm thick layer with \( N_A = 3.5 \times 10^{16} \text{ cm}^{-3} \).
  - annealing at 400°C for one hour in argon.
  - extended wavelength response.
  - responsivity = 0.5 A/W, dark current < 10⁻¹⁴ A, at bias = 100 mV and \( T = 2.0 \text{ K} \). \( \text{NEP} \approx 4 \times 10^{-16} \text{ W/√Hz} \).
Fig. 15. Responsivity of a Ge BIB detector, low energy B⁺-implant type. Active layer depth = 0.6 μm, [B] = 1 × 10¹⁶ cm⁻³, λ_filter = 98.9 μm, f_chopper = 23 Hz
Fig. 16. Spectral response of Ge BIB detector, low energy B⁺-implantation type.
• High energy B⁺-implantation tests:

  - 14 implant energies up to 4 MeV doubly charged boron ions lead to a 5 μm thick layer with $N_A = 1 \times 10^{16} \text{cm}^{-3}$.

  - Variable temperature Hall effect and resistivity measurements indicate full activation of shallow acceptor dopant B. No deep levels are detectable after annealing. Below 15 K, hopping conduction becomes dominant.

  - Infrared transmission measurements and device tests are in progress.
Fig. 17. Ge BIB, high energy ion implant profile
Fig. 18. Free carrier freeze-out of high energy B⁺-implanted layer. Before annealing (+), the slope of the freeze-out curve is steeper than after annealing (*). The latter slope corresponds to ~10.4 meV, the binding energy of shallow boron acceptors. Below 15 K, hopping conduction becomes dominant.
Fig. 19. Resistivity as a function of inverse temperature of the high energy B$^+$-implant layer before (+) and after (⋆) annealing. Hopping conduction becomes dominant below 15 K.
4. CONCLUSIONS

- A LPVPE technique for the low temperature growth of epitaxial Ge layers has been developed.

- Hall effect and resistivity measurements indicate that the epi layers are lightly p-type due to residual copper contamination.

- First generation Ge BIB detectors made with moderately doped substrates \((5 \times 10^{15} \text{ cm}^{-3})\) exhibit effective blocking of the hopping current.

- First generation Ge BIB detectors exhibit responsivities around 1 A/W.

- Second generation devices using low pressure VPE are being processed.

- Ion implanted active layers are tested.

- It is currently not known what temperatures will be required to reduce the dark current down to levels which are acceptable for SIRTF applications.