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GERMANIUM BLOCKED IMPURITY BAND (BIB) DETECTORS

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CONTENTS

1. INTRODUCTION

- Extrinsic, photoconductive semiconductor detectors cover the infrared spectrum from a few μm up to 250 μm.

- 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?**

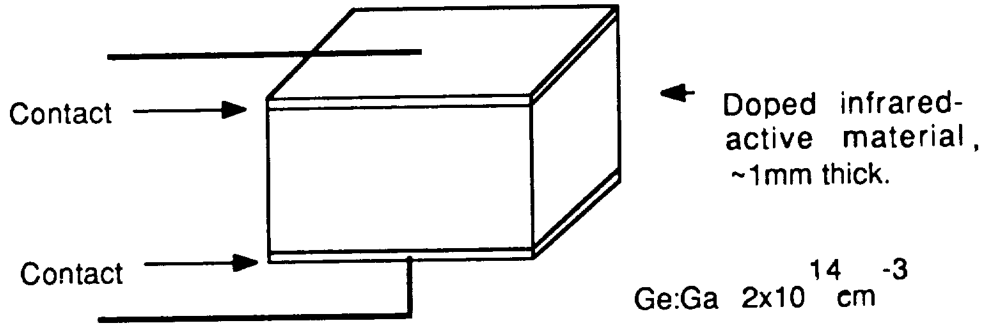


Figure 1(a). Schematic of conventional detector.

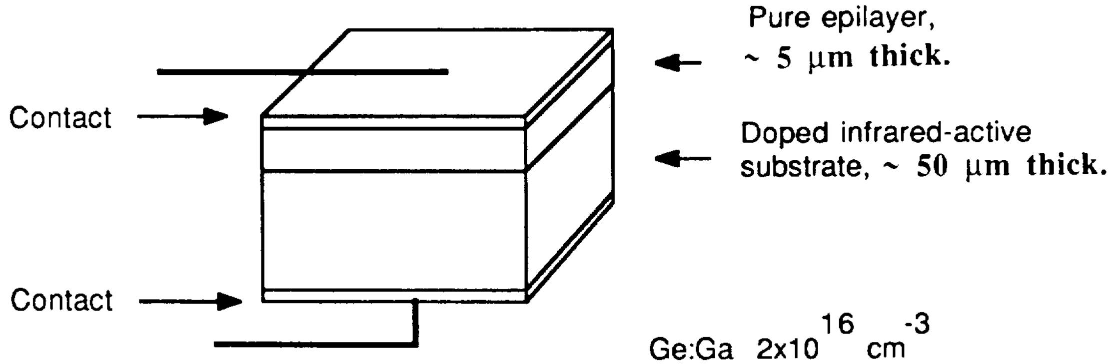


Figure 1(b). Schematic of BIB detector.

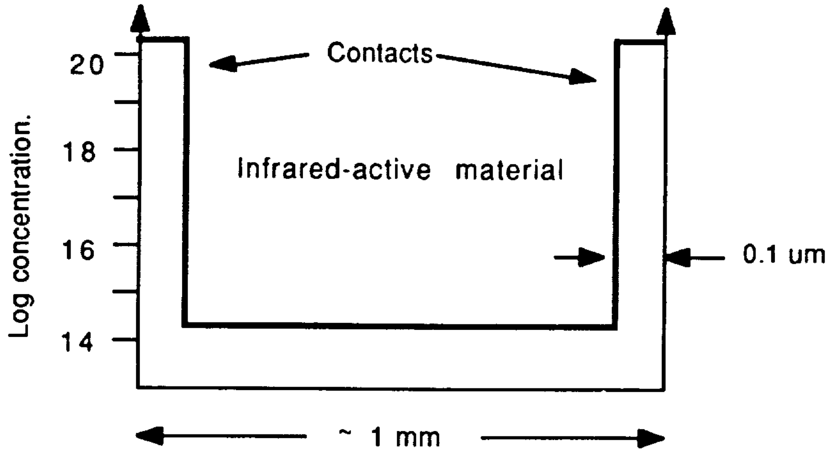


Figure 2(a). Doping levels in a conventional Ge detector.

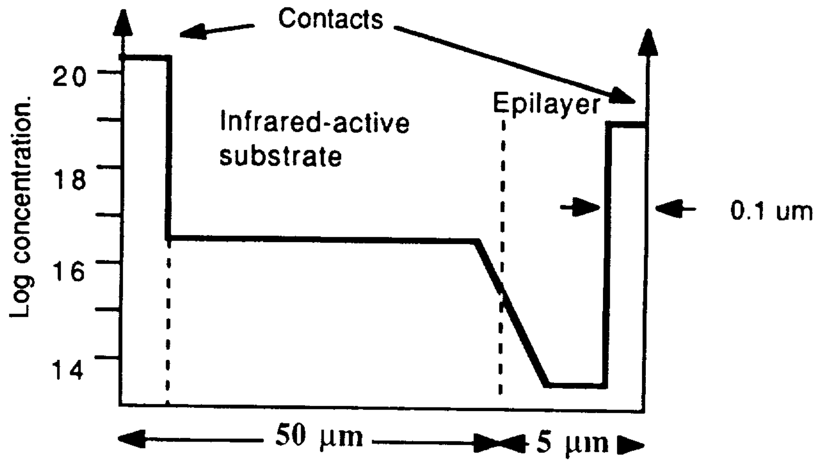
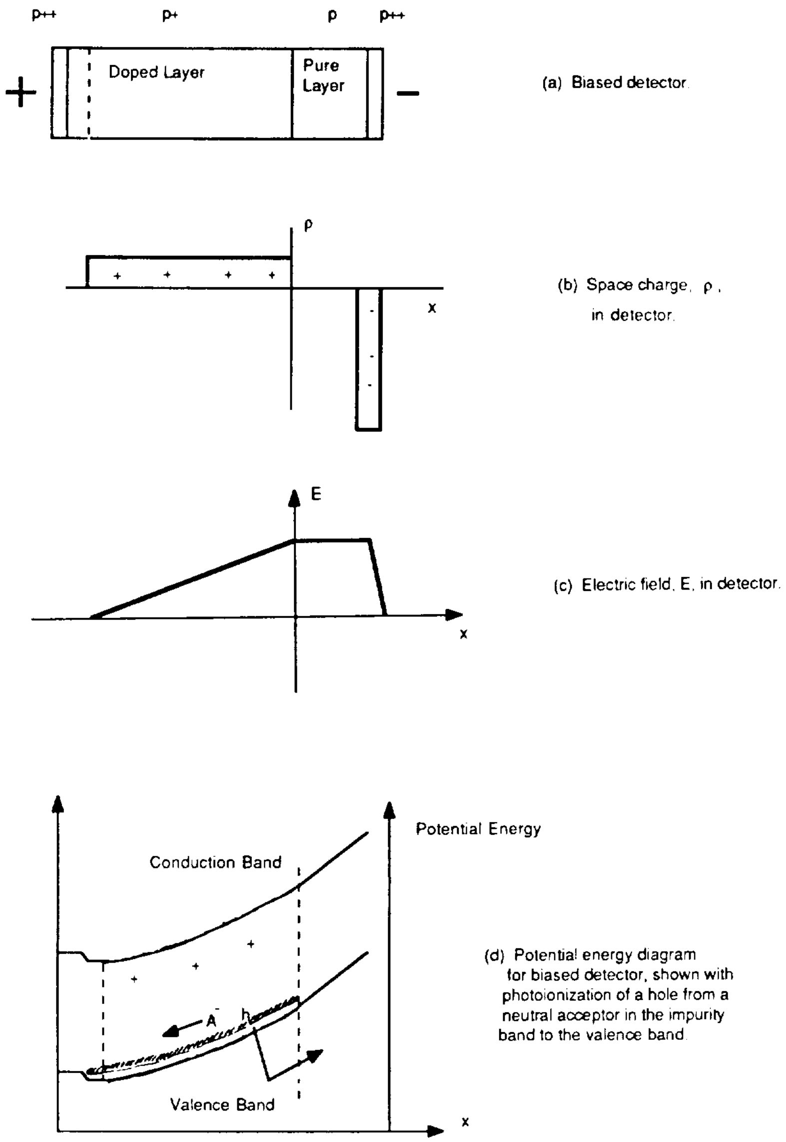


Figure 2 (b). Doping levels in a Ge BIB detector.



(a) Biased detector.

(b) Space charge, ρ, in detector.

(c) Electric field, E, in detector.

(d) Potential energy diagram for biased detector, shown with photoionization of a hole from a neutral acceptor in the impurity band to the valence band.

Fig. 3. Schematics of space charge, electric field and potential energy for a reverse biased p-type BIB detector.

3. <u>Ge BIB DETECTOR DEVELOPMENT</u>

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 [$Ge(CH_3)_4$, $Ge(C_2H_5)_4$] 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 x 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 H_2O_2.**
  - **brief etch in HNO_3:HF (3:1) followed by soak in HF (1% in H_2O) to remove oxides.**
- **Epitaxy:**
  - **first experiments with atmospheric pressure vapor phase epitaxy (VPE). Disadvantage: high substrate temperature, 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.**

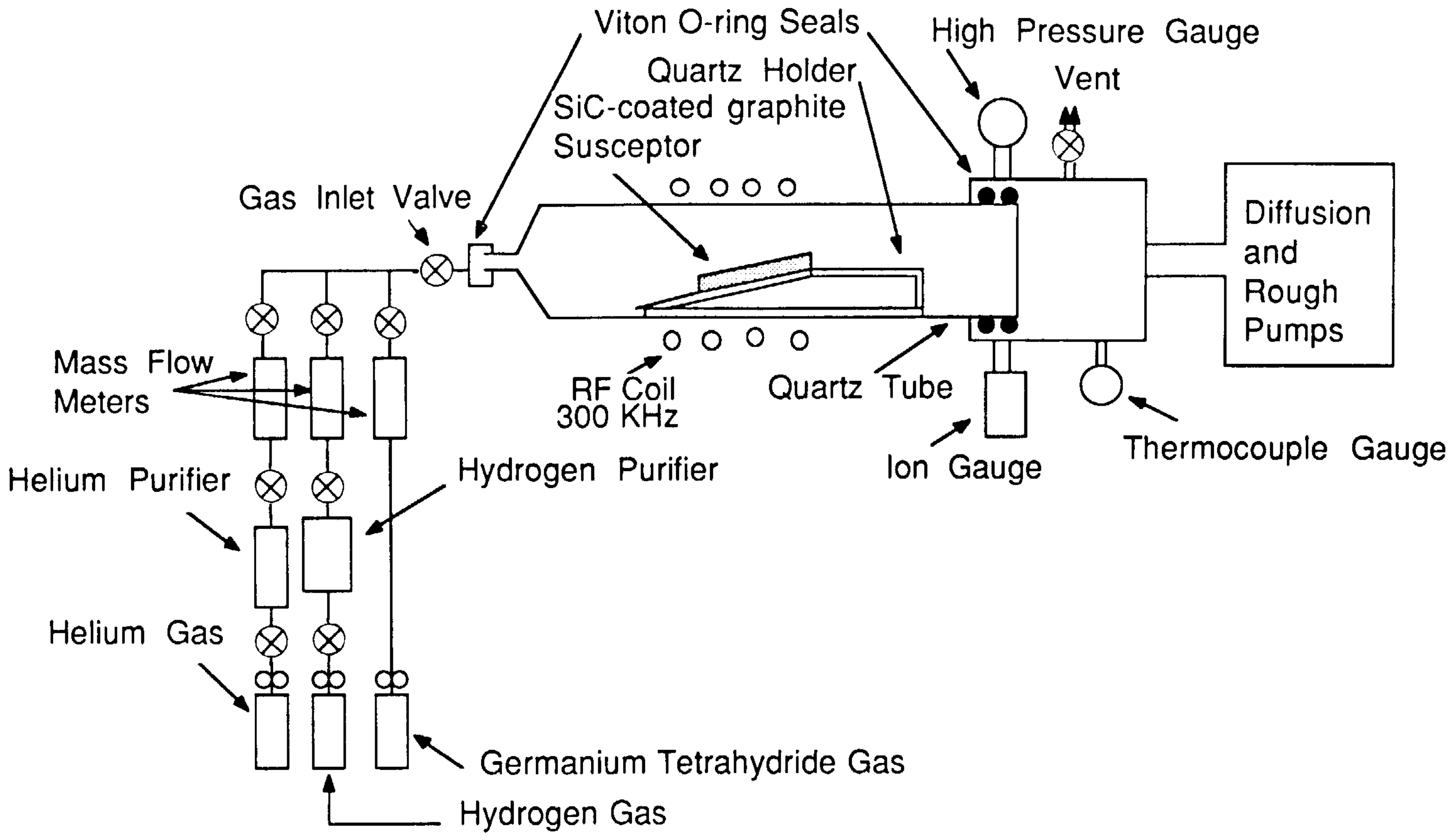


Fig. 4. Schematic of horizontal VPE apparatus. Quartz tube is 5.7 cm O.D. x 75 cm long.

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**

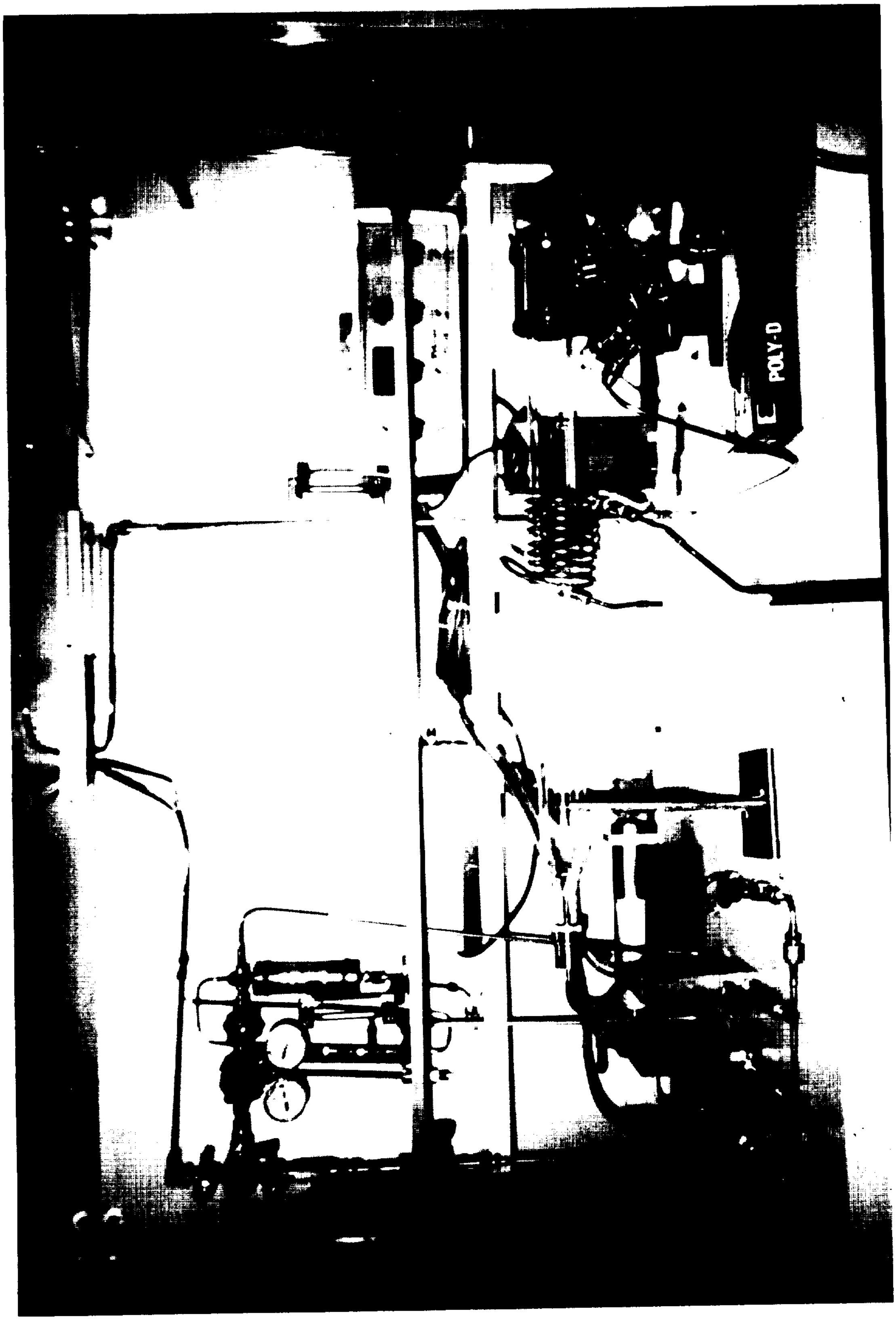
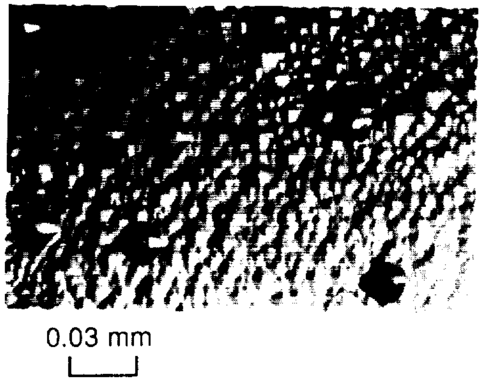
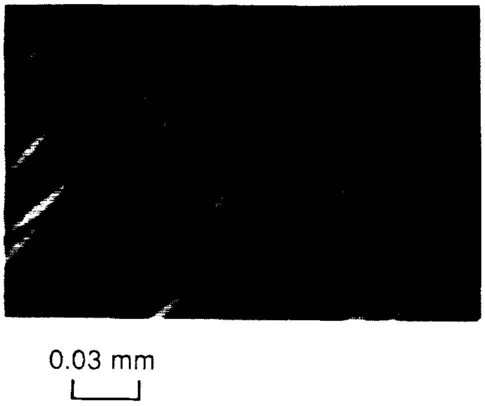


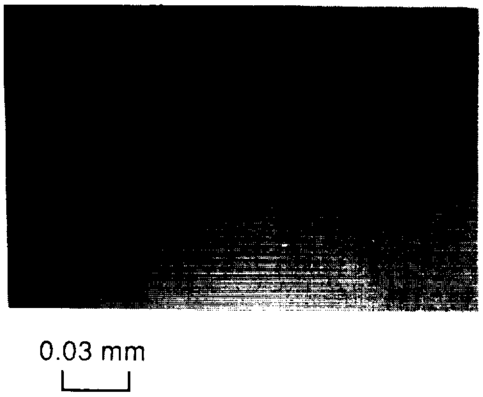
Fig. 5. Photograph of the horizontal VPE chamber.



(100) $N_D - N_A = 1 \times 10^{14} / cm^3$
580 °C; 5 sccm GeH_4,
with H_2 reduction step,
polycrystalline deposition



(113) $N_D - N_A = 2 \times 10^{14} / cm^3$
580 °C; 5sccm GeH_4,
with H_2 reduction step,
no growth (etching)



(113) $N_D - N_A = 5 \times 10^{11} / cm^3$
550 °C; 10sccm GeH_4,
no H_2 reduction step,
single crystal deposition

Fig. 6. Optical micrographs of Ge epi layers.

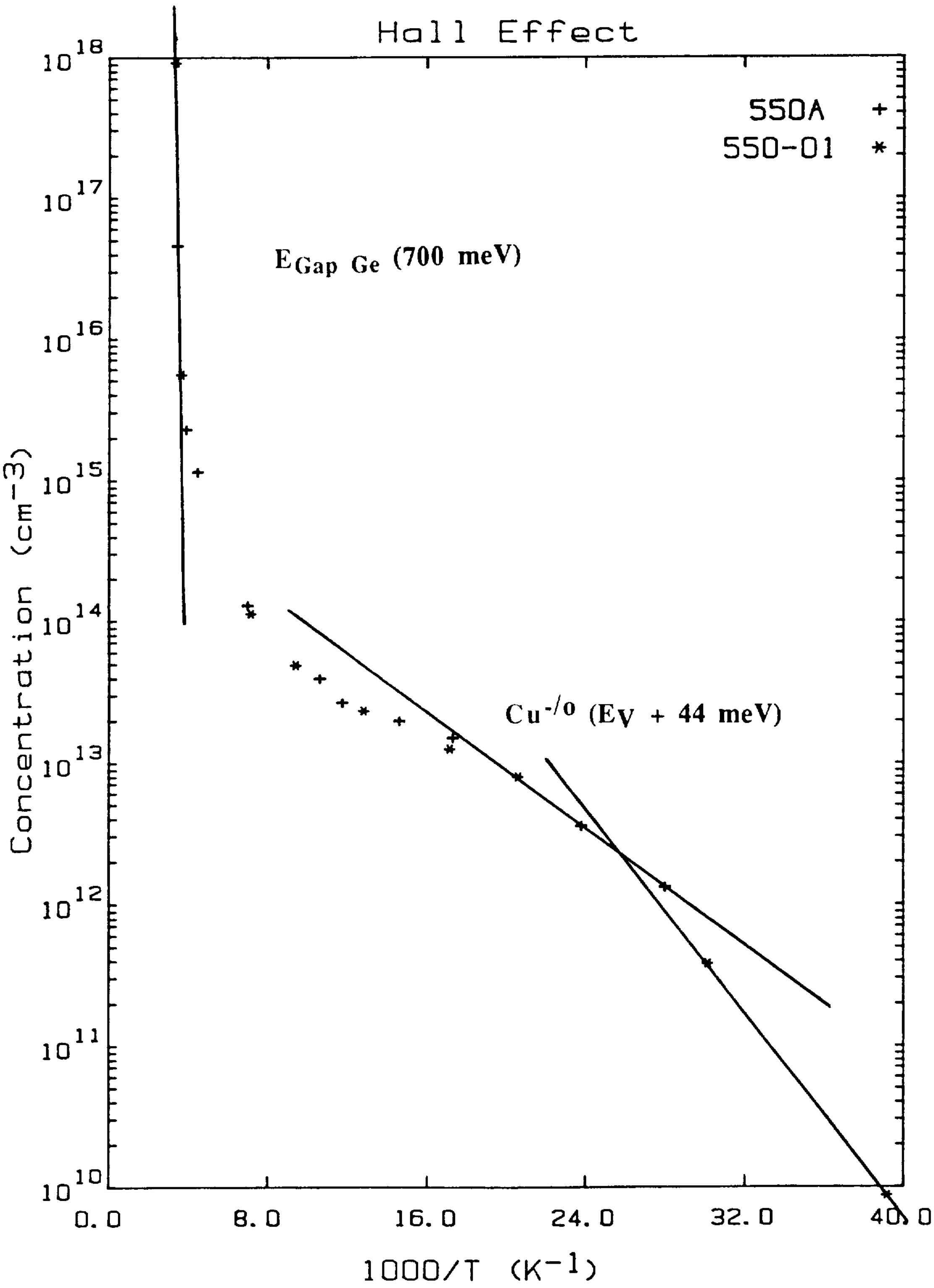


Fig. 7. Variable temperature Hall effect measurements of a Ge epilayer on an n-type [113] substrate. The hole freeze-out curves indicate a light copper contamination. The two curves (+, *) are measurements of the same sample and demonstrate reproducibility.

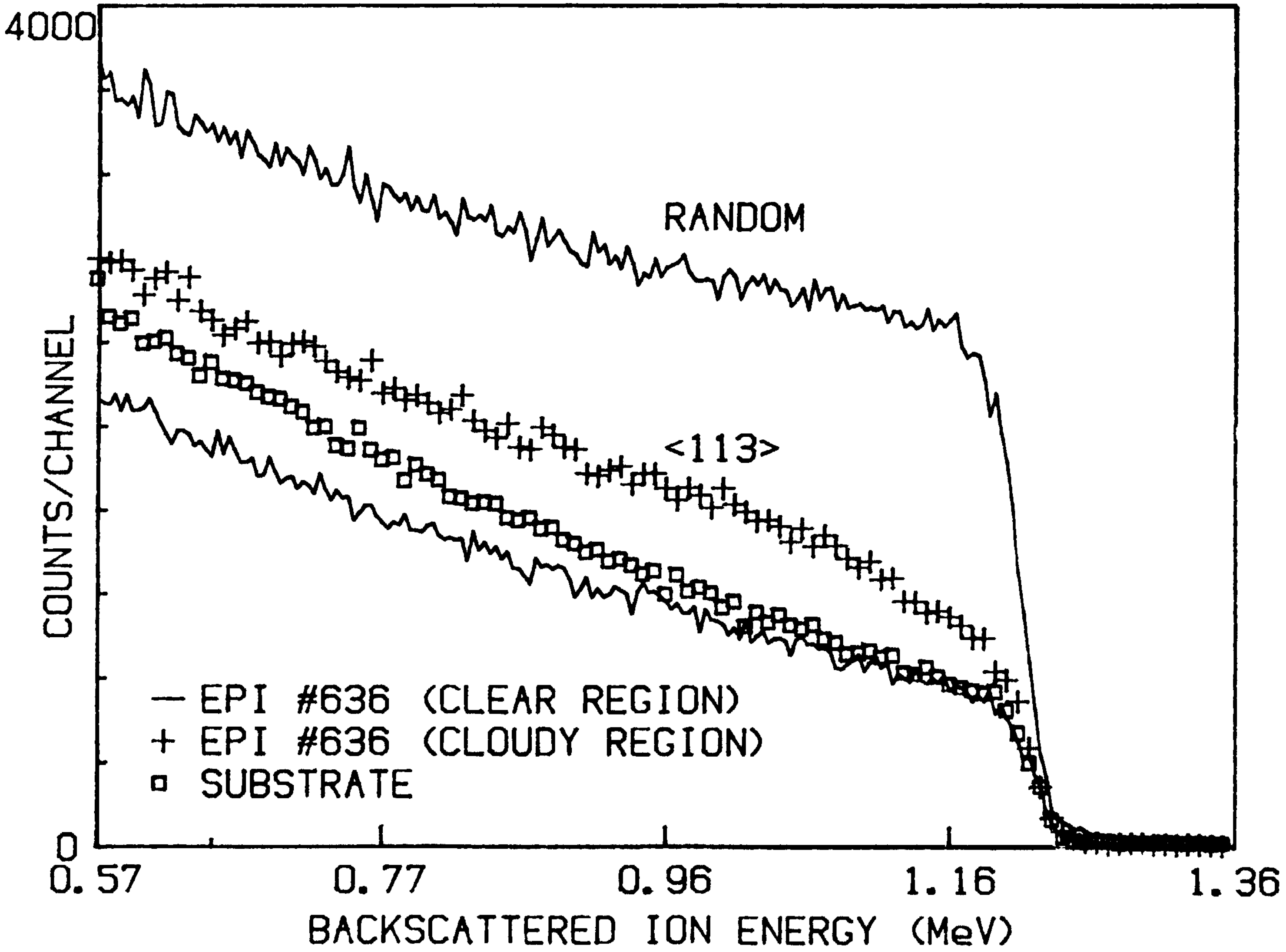


Fig. 8. RBS channeling spectra of a Ge epi film (#636). The "cloudy" region shows significant dechanneling indicating a high defect concentration.

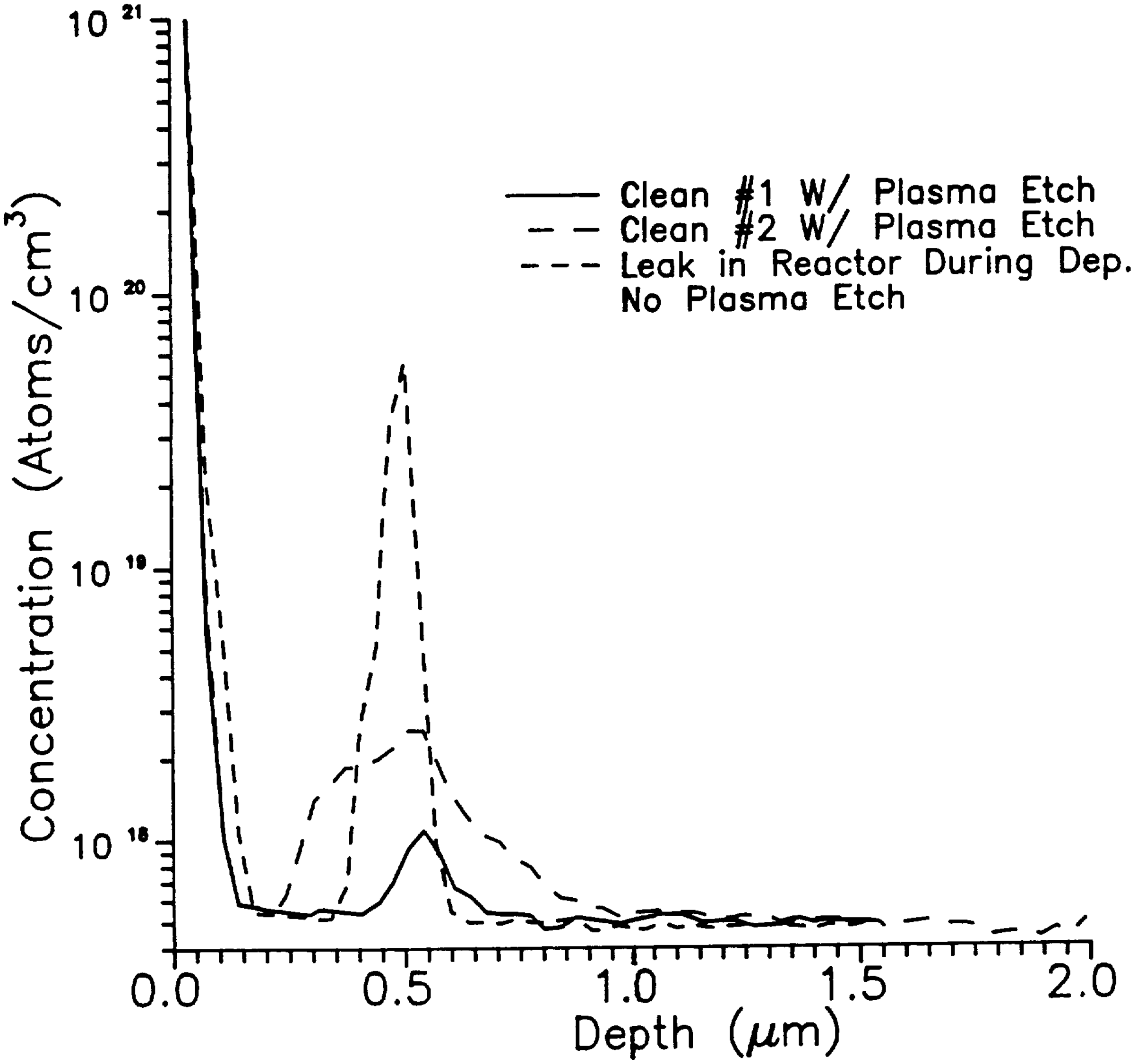


Fig. 9. SIMS of LPVPE Epi Films: Oxygen Concentration

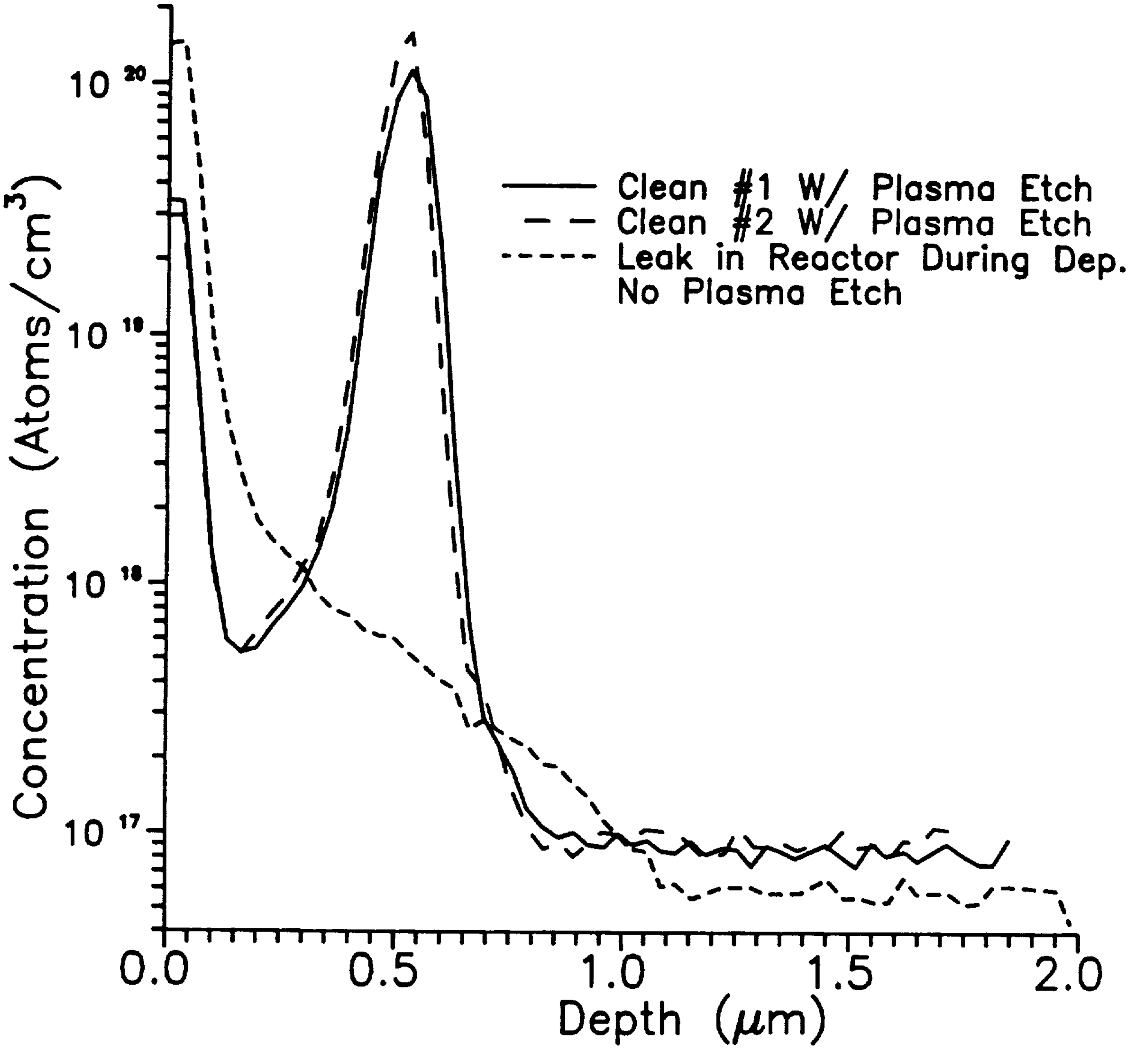


Fig. 10. SIMS of LPVPE Epi Films: Carbon Concentration

3.1.3. Preliminary detector test results

- **Responsivity**
- **Dark current**

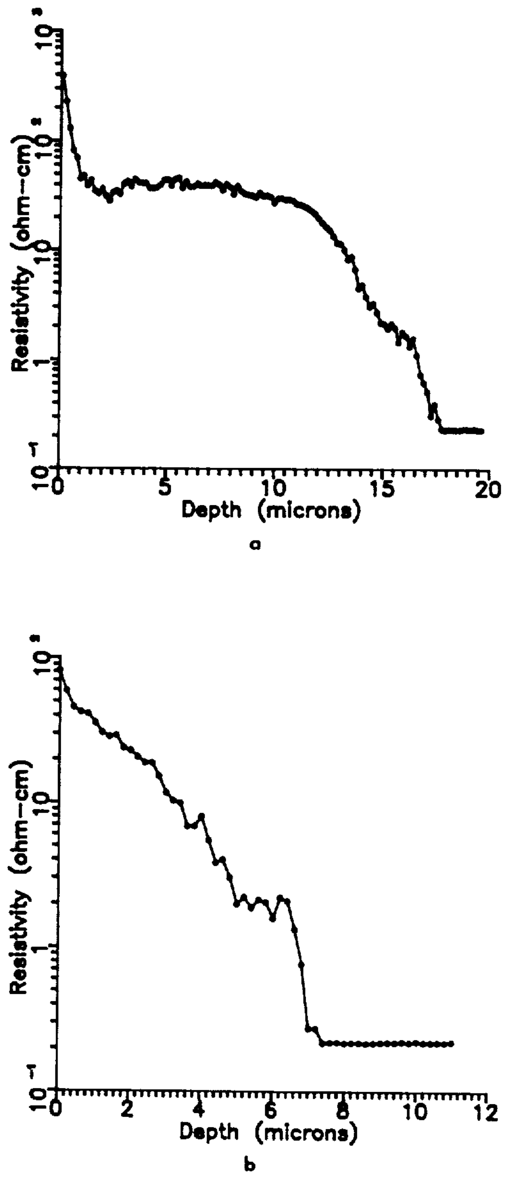


Fig. 11. Spreading resistance as a function of depth from the epilayer surface for: (a) an area of epilayer close to the leading edge of the wafer in II-16 where the growth rate was ~ 0.06 μmmin^{-1}, and (b) an area of epilayer farthest from the leading edge of the same wafer where the growth rate was ~ 0.02 μmmin^{-1}. The slight rise in resistivity at the very surface is due to the native oxide.

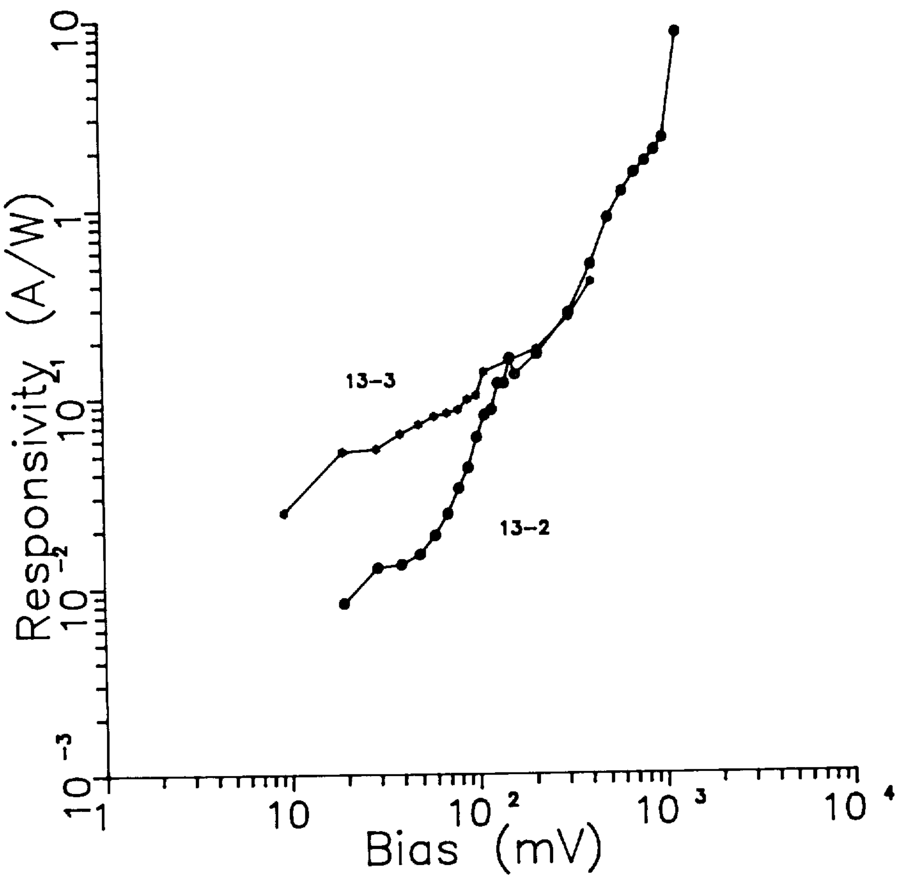


Fig. 12. Responsivity as a function of bias for detectors 13-2 and 13-3 at 2.3 K under reverse bias. The substrate material is moderately doped (5 x 10^{15} cm^{-3}). Such material exhibits hopping conduction but does not have extended wavelength spectral response. Tests were performed with a narrow band filter at λ = 98.9 μm.

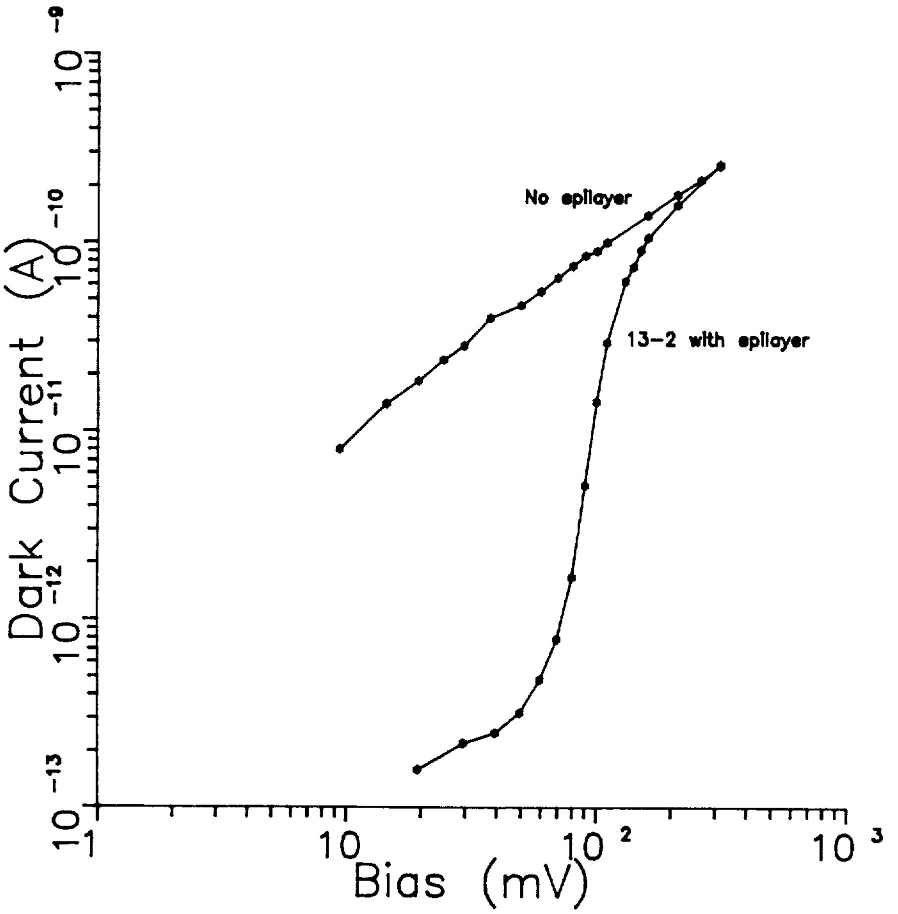


Fig. 13. Dark current as a function of detector bias for detector 13-2 with an epilayer and for the same "detector" without an epilayer at 2.3 K under reverse bias. Below a bias of ~ 100 mV, the blocking layer effectively reduces hopping conduction in this moderately doped material ($N_A - N_D = 5 \times 10^{15}$ cm^{-3}).

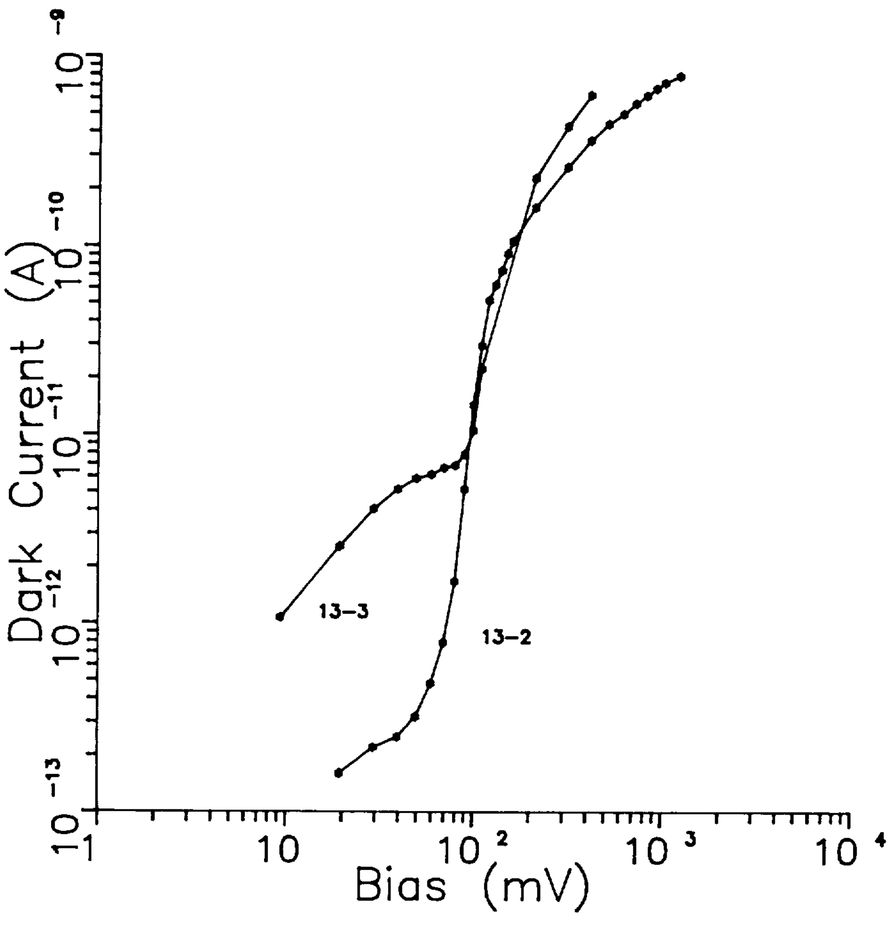


Fig. 14. Dark current as a function of bias for detectors 13-2 and 13-3 at 2.3 K under reverse bias.

3.2. Ion Implanted 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 $N_A = 3.5 \times 10^{16}$ 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 K. NEP $\approx 4 \times 10^{-16}$ W/ $\sqrt{\text{Hz}}$.**

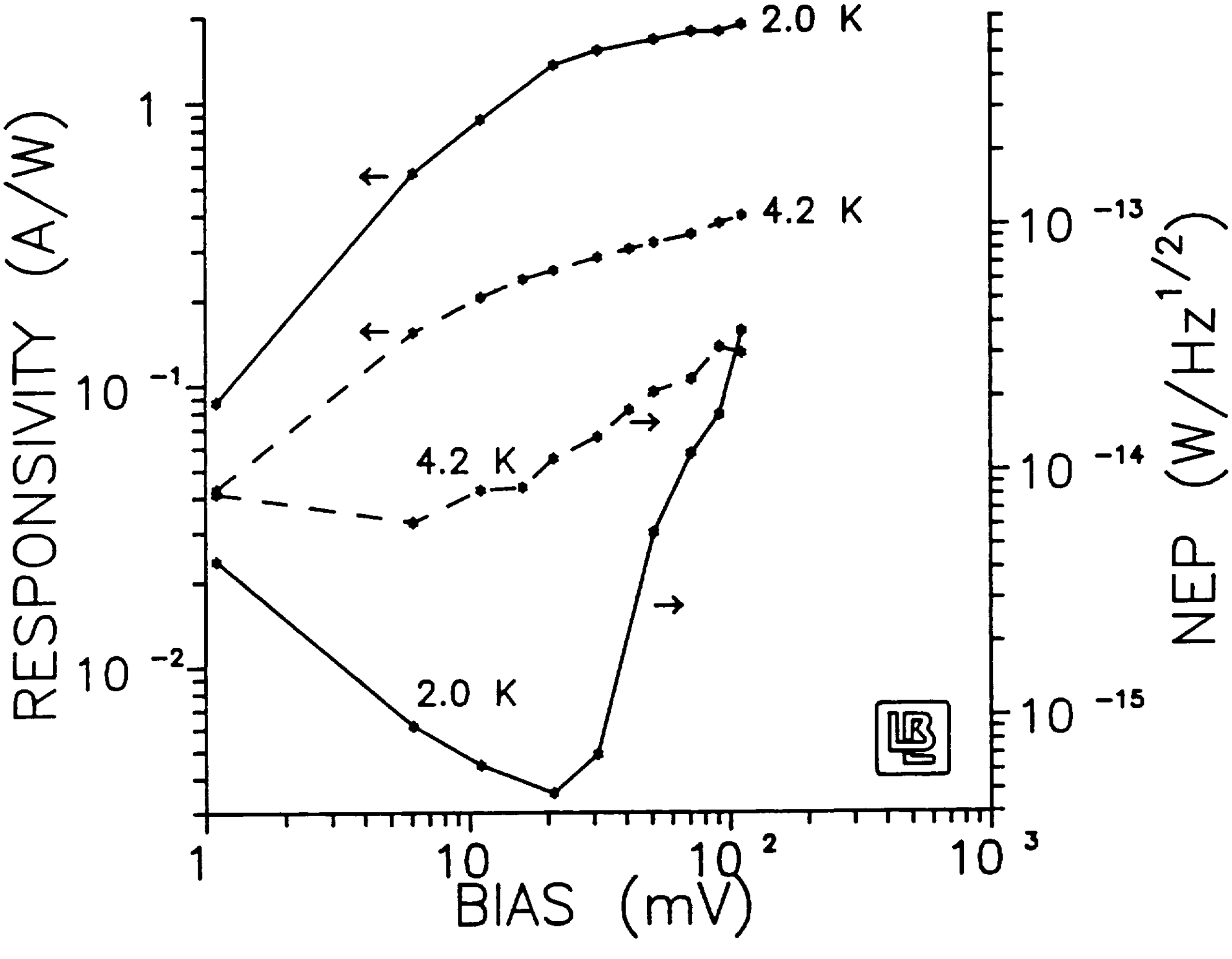


Fig. 15. Responsivity of a Ge BIB detector, low energy B^+−implant type. Active layer depth = 0.6 μm, [B] = 1 X 10^{16}cm^{-3}, λ_{filter} = 98.9 μm, $f_{chopper}$ = 23 Hz

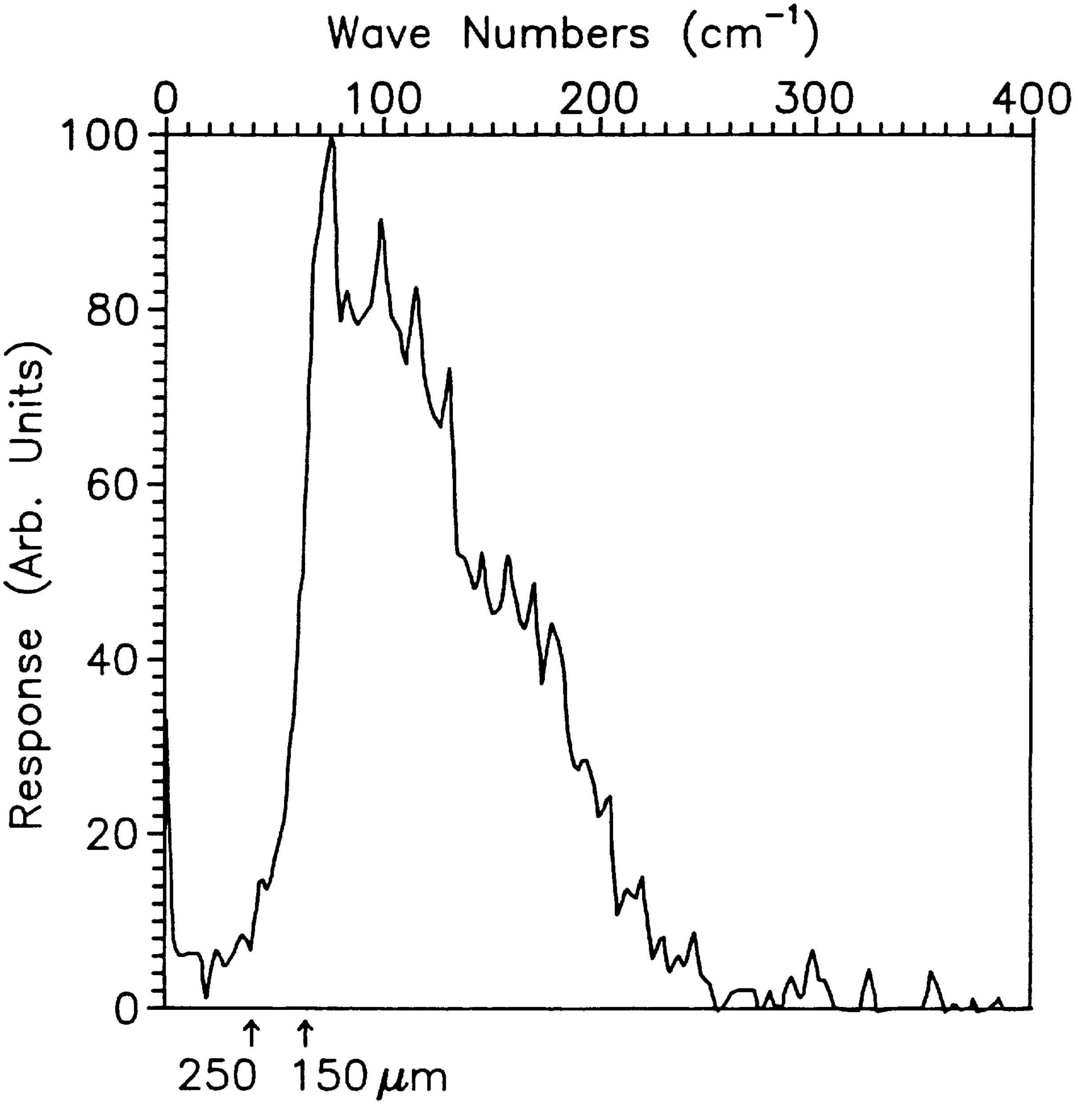


Fig. 16. Spectral response of Ge BIB detector, low energy B^+–implantation type.

- 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 = 1×10^{16} 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.

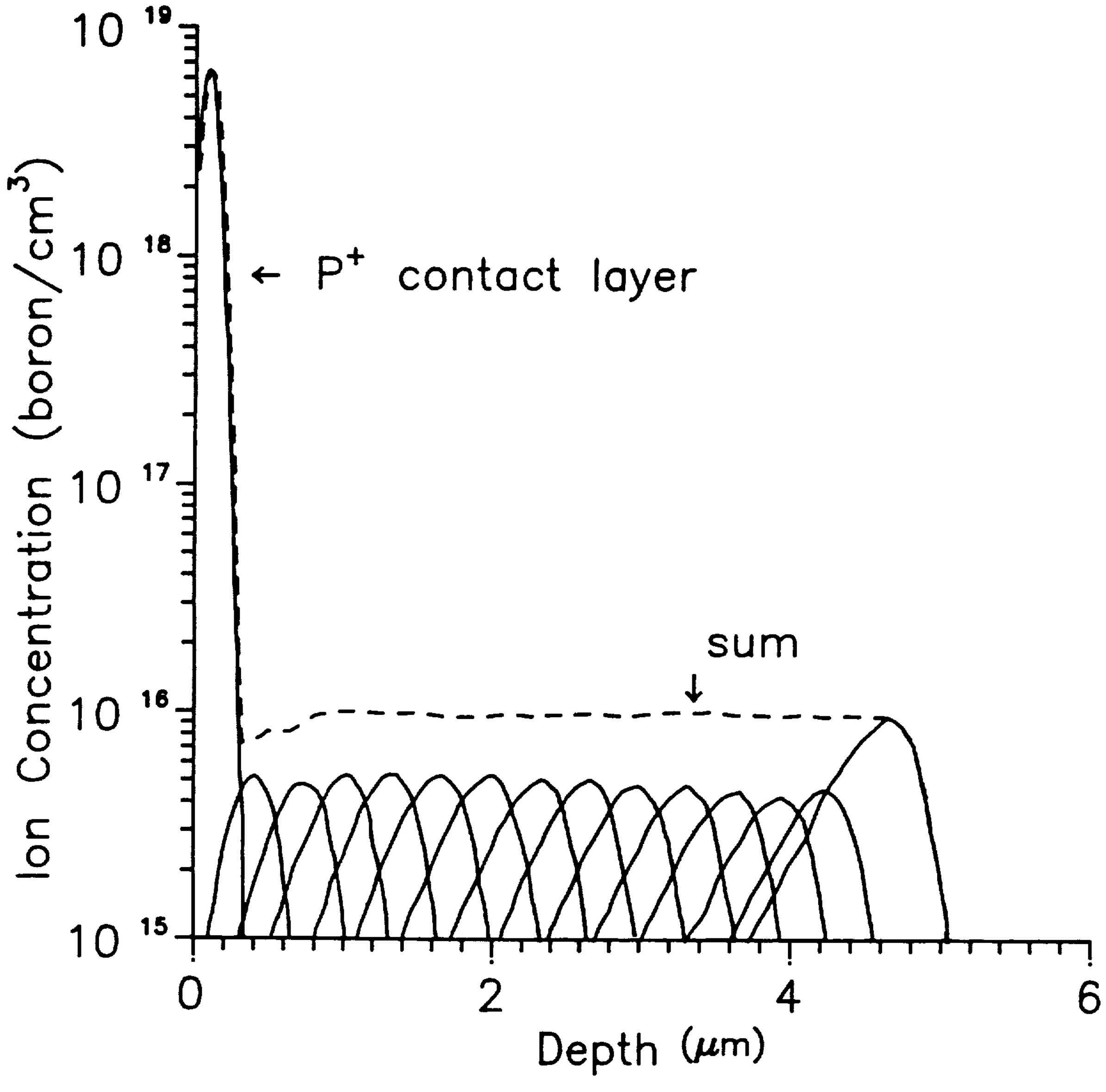


Fig. 17. Ge BIB, high energy ion implant profile

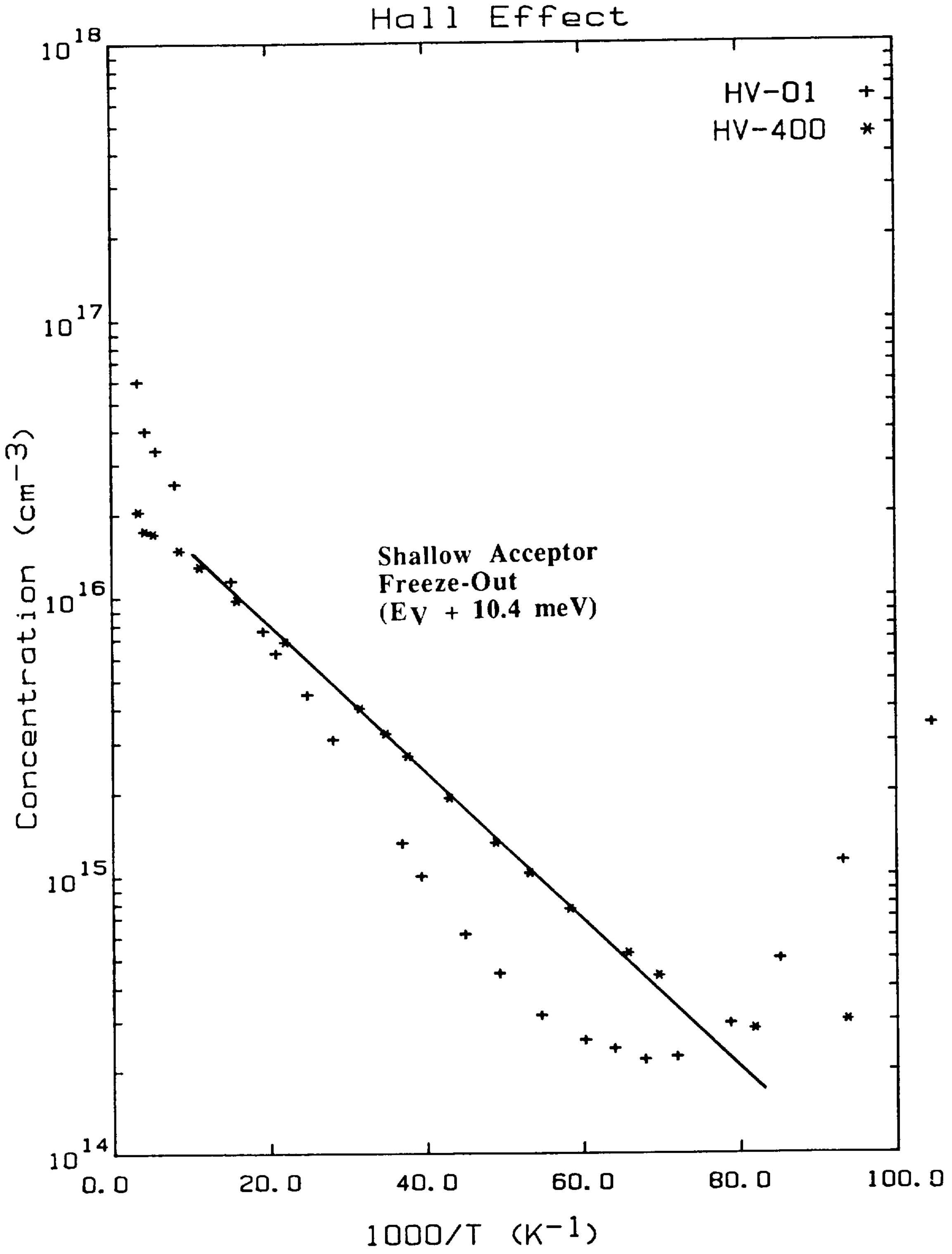


Fig. 18. Free carrier freeze-out of high energy B^+-implanted layer. Before annealing (+), the slope of the freeze-out curve is steeper than after annealing (*). The latter slope corresponds to ~ 10.4 meV, the binding energy of shallow boron acceptors. Below 15 K, hopping conduction becomes dominant.

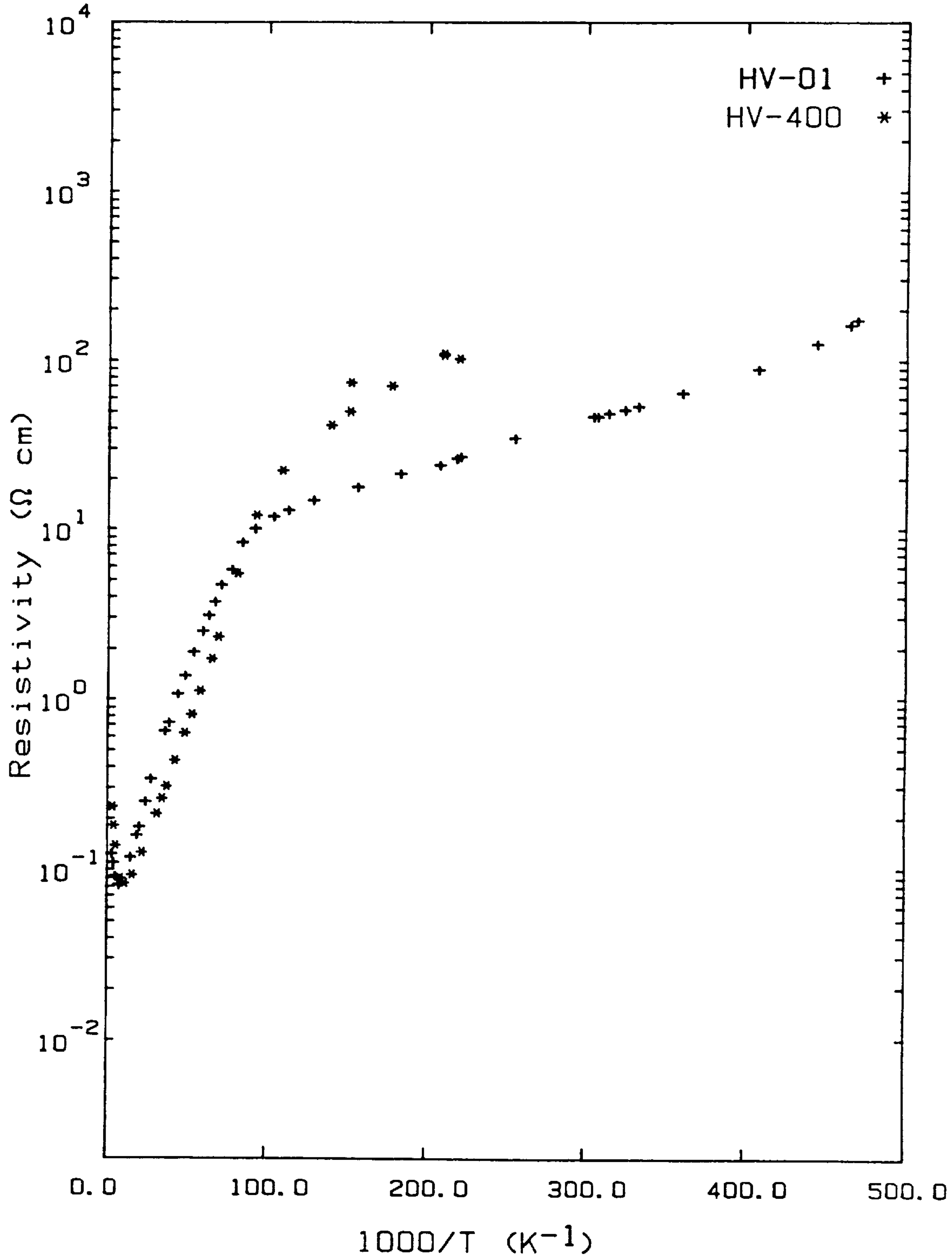


Fig. 19. Resistivity as a function of inverse temperature of the high energy B^+-implant layer before (+) and after (∗) annealing. Hopping conduction becomes dominant below 15 K.

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 (5×10^{15} 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.