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IR Detectors based on n-i-p-i Superlattices

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It has been demonstrated that the internal electric fields present in n-i-p-i doped semiconductor superlattices give rise to interband photo absorption well below the bandgap of the host semiconductor material. In addition, the internal fields separate the photo generated electrons and holes resulting in large non-equilibrium charge carrier lifetimes and, consequently, in large photoconductive gain. Experimental results on GaAs n-i-p-i superlattices have confirmed these expectations for photon wavelengths in the near infrared ($\lambda < 1.5$ μm). For an extension of the wavelength range to the mid and far infrared, semiconductors with smaller bandgaps are more suitable than GaAs as n-i-p-i superlattice host materials. Strong candidate materials are InAs and InSb because of their favorable growth and doping properties.

In this paper the principles of operation of n-i-p-i photodetectors will be discussed. Special consideration is given to issues that are relevant to the performance of IR detectors such as noise, dark current, and surface effects. In addition, we will discuss a novel IR detector that promises to provide information about the spectral distribution of the infrared radiation emitted from an object and, consequently, about its temperature, independent of the distance between detector and object. This detector makes use of the possibility to modulate the internal electric fields of an n-i-p-i superlattice with an applied voltage. By this technique the spectral responsivity of the detector may be controlled electrically and some information about the shape of the emission spectrum may be obtained.

IR DETECTORS BASED ON DOPING SUPERLATTICES

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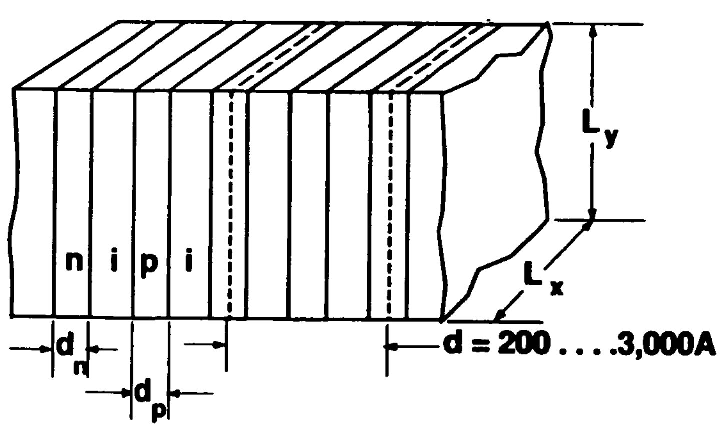
Outline

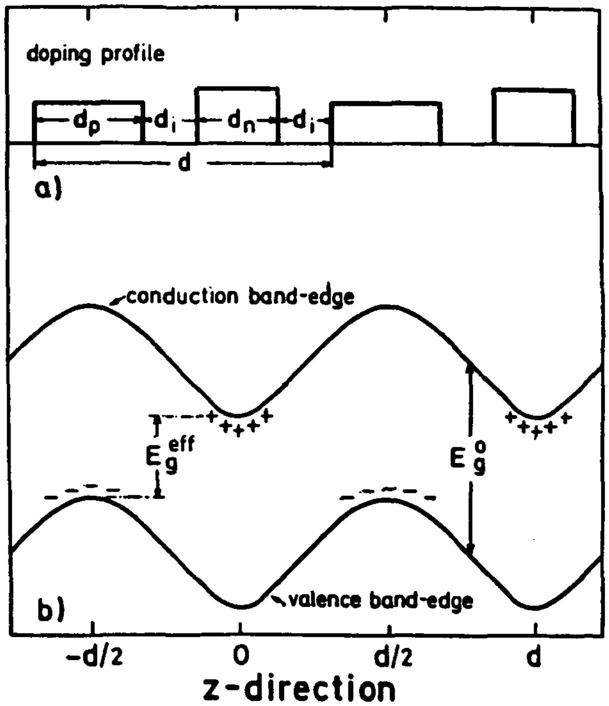
- Introduction, optical absorption in nipi SL
- Electroabsorption GaAs, InAs, InSb
- Noise in nipi detectors
- Spectrally agile detector
- Inhomogeneous excitation and surface effects
- Summary

Doping Superlattice (n-i-p-i)

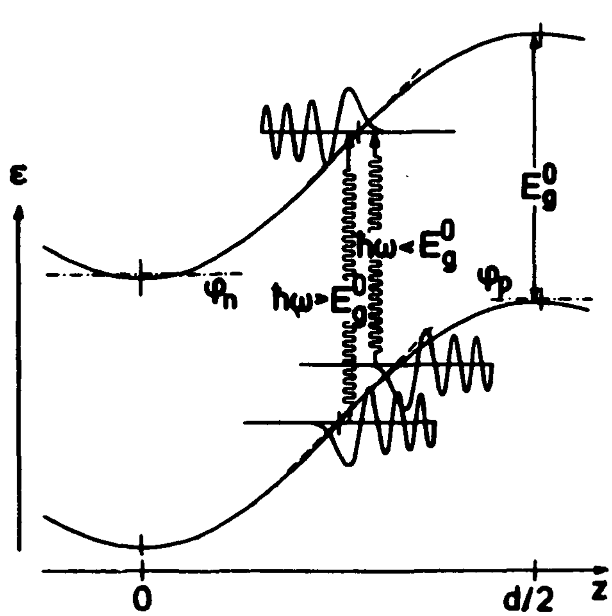


Materials: GaAs, AlGaAs, InP, GaP, InAs, InSb, InGaAs, PbTe, Si,...?

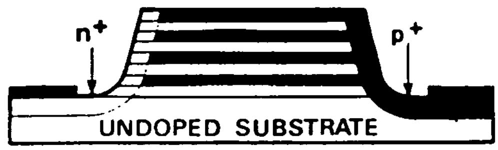
Schematic Doping Profile and Band Diagram of NIPI Superlattice

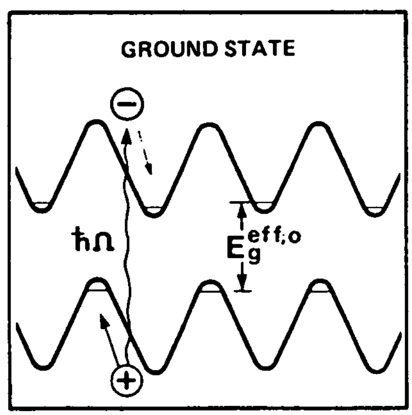


Photon Absorption in Doping Superlattice



DOPING SUPERLATTICE PHOTODETECTOR





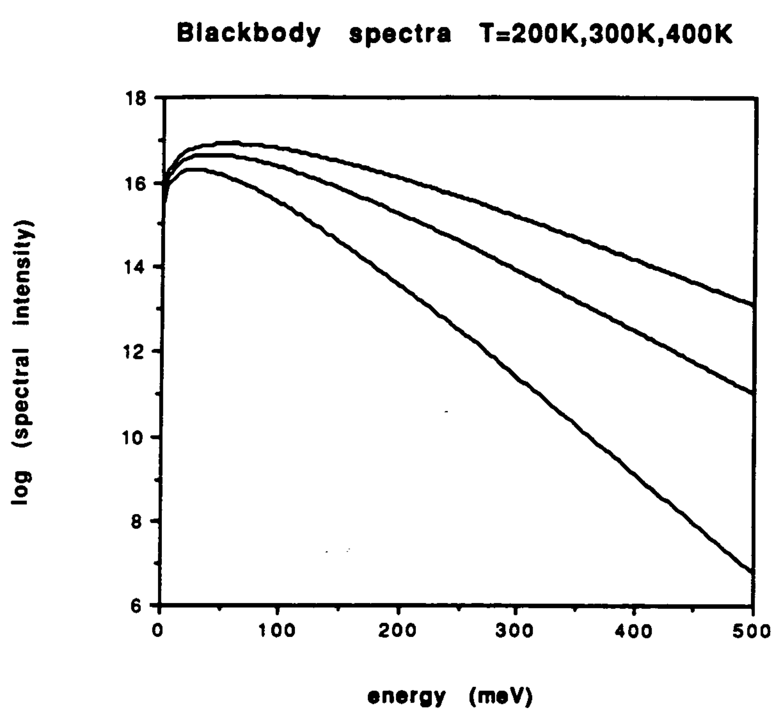
Two modes of operation:

1) Photovoltaic mode:

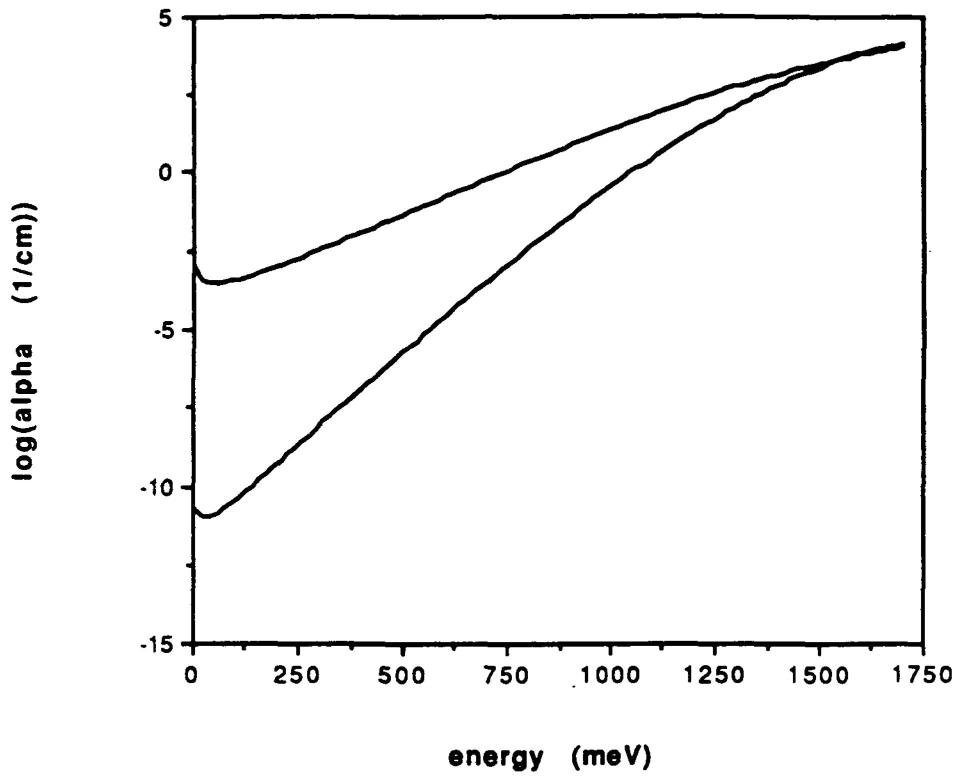
δI_{np}

2) Photoconductive mode:

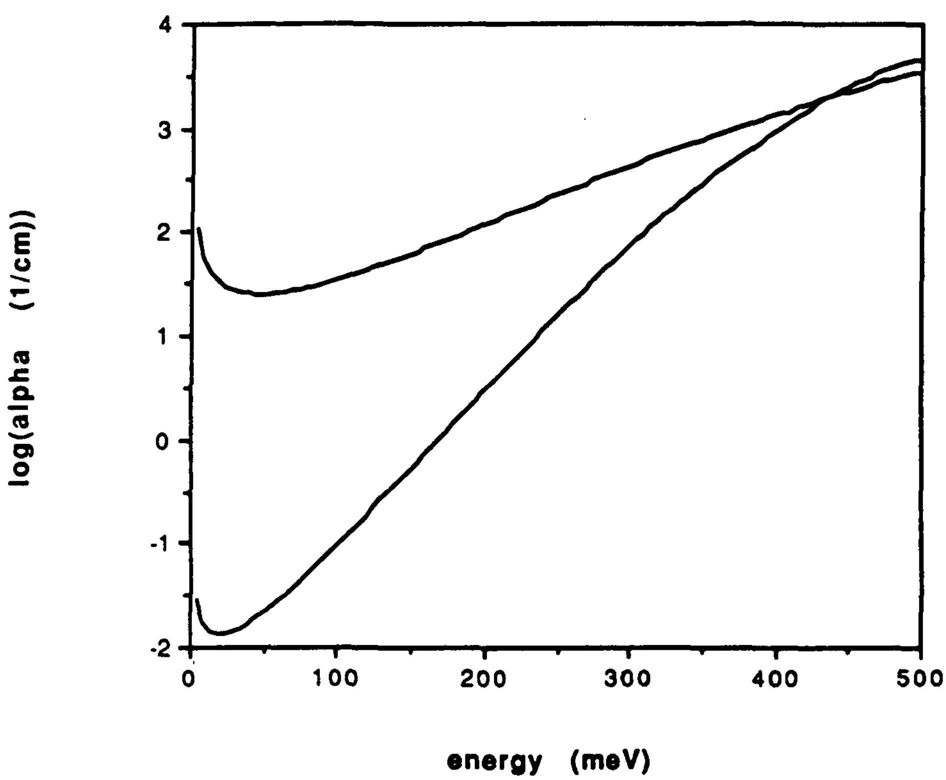
δI_{nn} or δI_{pp}

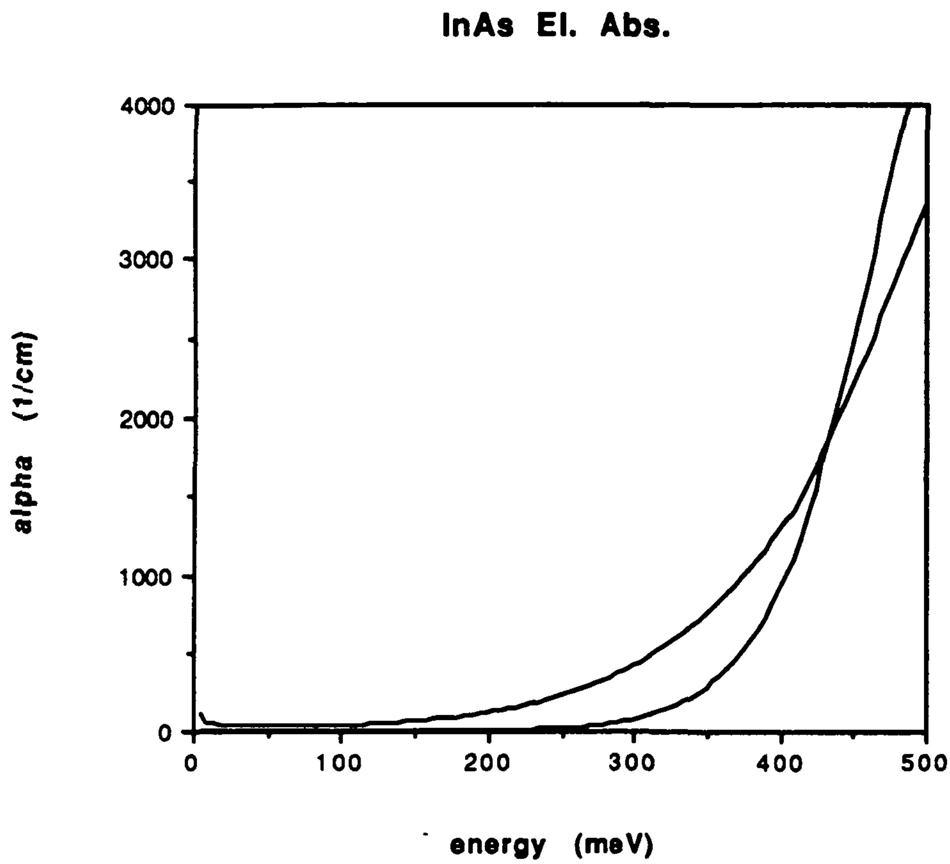


GaAs El. Abs. T=77K

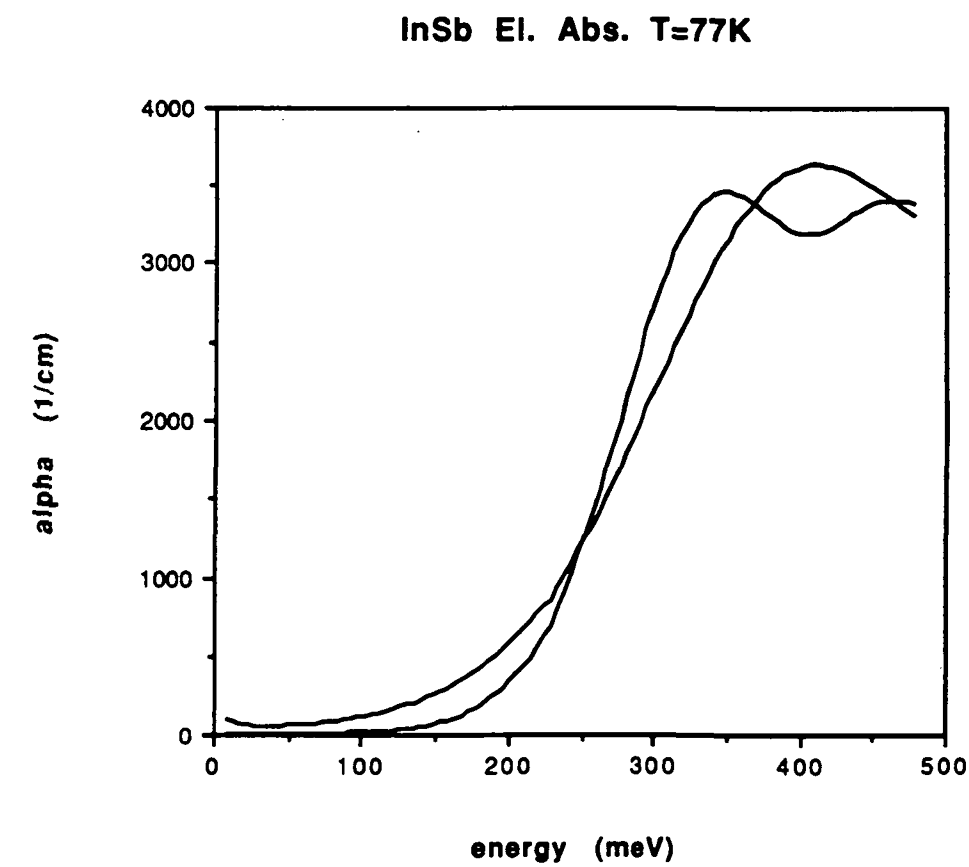


InAs El. Abs.

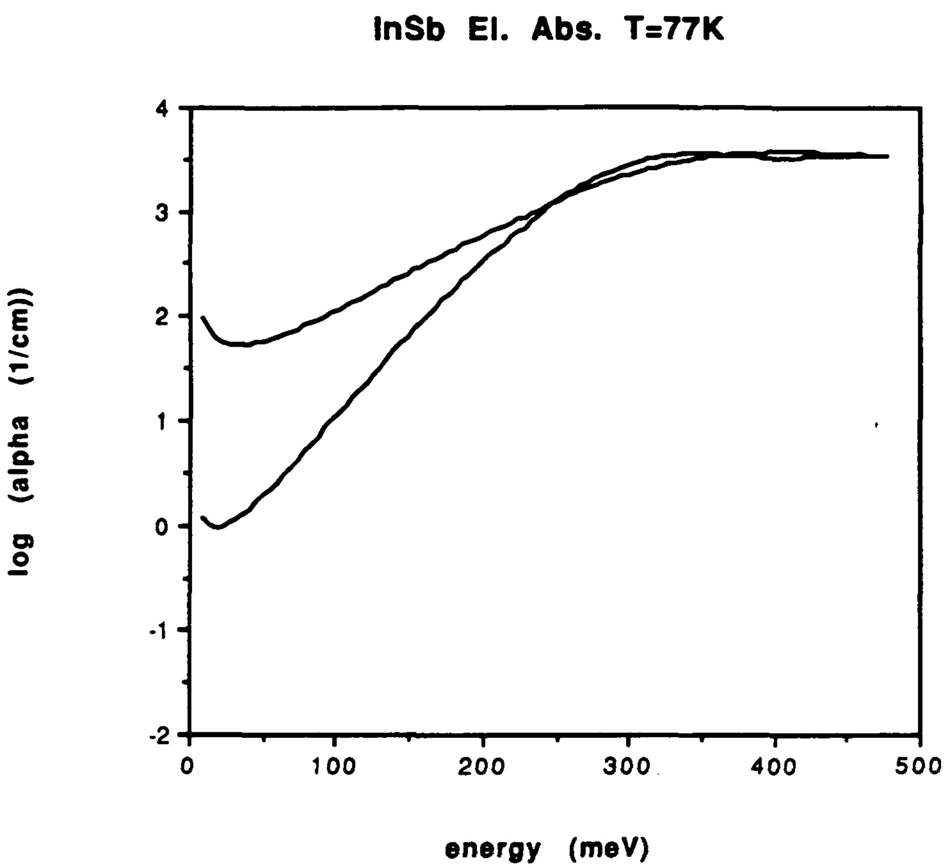




InAs El. Abs.
4000
3000
2000
1000
0
alpha (1/cm)
0
100
200
300
400
500
energy (meV)



InSb El. Abs. T=77K
4000
3000
2000
1000
0
alpha (1/cm)
0
100
200
300
400
500
energy (meV)



<u>Example</u>

InSb nipi BLIP $\qquad n_D^{(2)} = 3.5\times10^{12}\ cm^{-2}$

$d_i = 100$ A

$\rightarrow F_{bi}d_i \sim E_g^o$

$\hbar\omega_o = 108$ meV $\triangleq \lambda_o = 11.5\ \mu m$, $T_B = 300K$

$\alpha(\hbar\omega_o) = 130\ cm^{-1}$

$\bar{\alpha} = 51\ cm^{-1}$ with cut-off $\hbar\omega_c = 100$ meV $\quad D^* = 2.6\times10^8 \sqrt{N_{SL}}\ cm \sqrt{Hz}/W$

$\bar{\alpha} = 107\ cm^{-1}$ without cut-off $\quad D^* = 1.8\times10^8 \sqrt{N_{SL}}\ cm \sqrt{Hz}/W$

$N_{SL} = 1750 \rightarrow D^* = 1.1\times10^{10}\ cm \sqrt{Hz}/W$

compared to BLIP with $\eta = 1$ $\lambda_c = 11\ \mu m$ $\quad D^* = 3.4\times10^{10}\ cm \sqrt{Hz}/W$

Noise Sources in nipi IR Detectors

Detectivity

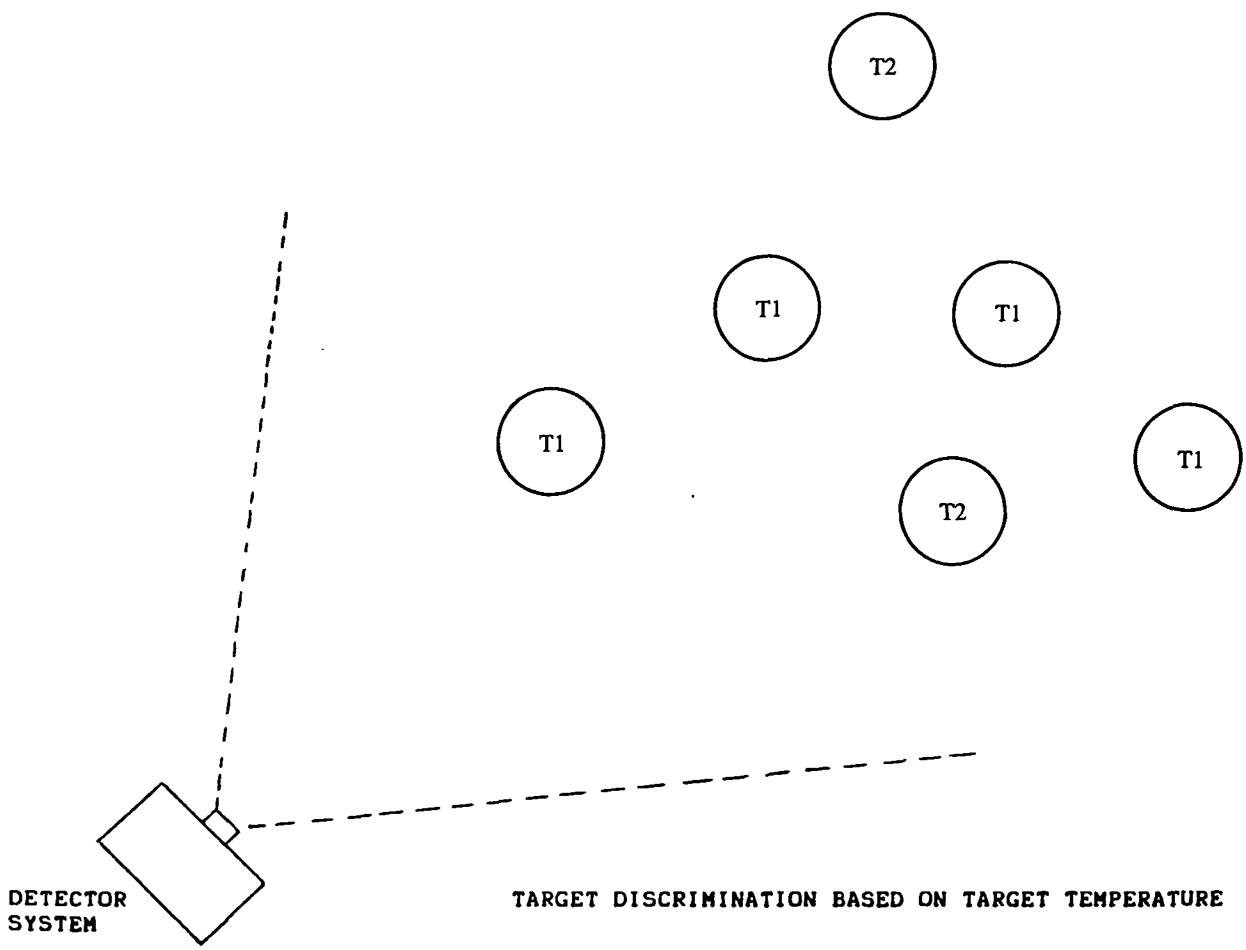
$$D^* = \sqrt{A}\ \frac{R}{I_{noise}}\ \sqrt{\Delta f}$$

Thermal g-r noise limited : $D^* = \frac{1}{2h\omega}\ \frac{\alpha(\omega)d_i}{\sqrt{p^{(2)}}}\ \sqrt{\tau}\ \sqrt{N_{SL}}$

$\bar{\alpha}\ d_i\ \sigma_\rho T_B^3 < p^{(2)}/\tau$

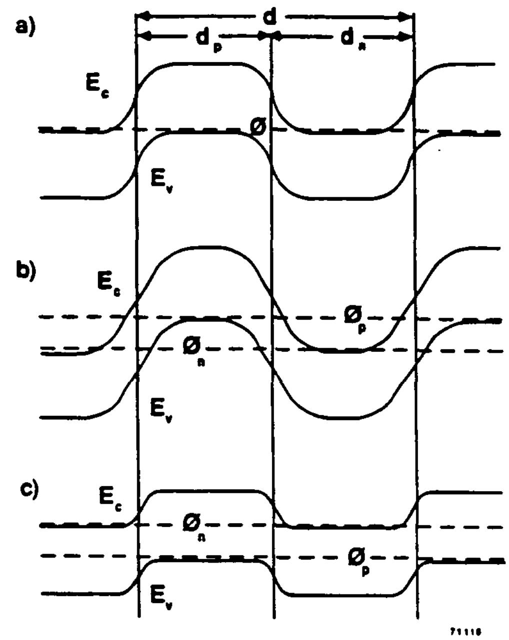
Background g-r noise limited : $D^* = \frac{1}{2h\omega}\ \frac{\alpha(\omega)}{(\bar{\alpha}\ \sigma_\rho T_B^3)^{1/2}}\ \sqrt{d_i}\ \sqrt{N_{SL}}$

$\bar{\alpha}\ d_i\ \sigma_\rho T_B^3 > p^{(2)}/\tau$ $\bar{\alpha} = \frac{\int dE\ \alpha(E) M_p(E,T_B)}{\sigma_\rho T_B^3}$



TARGET DISCRIMINATION BASED ON TARGET TEMPERATURE

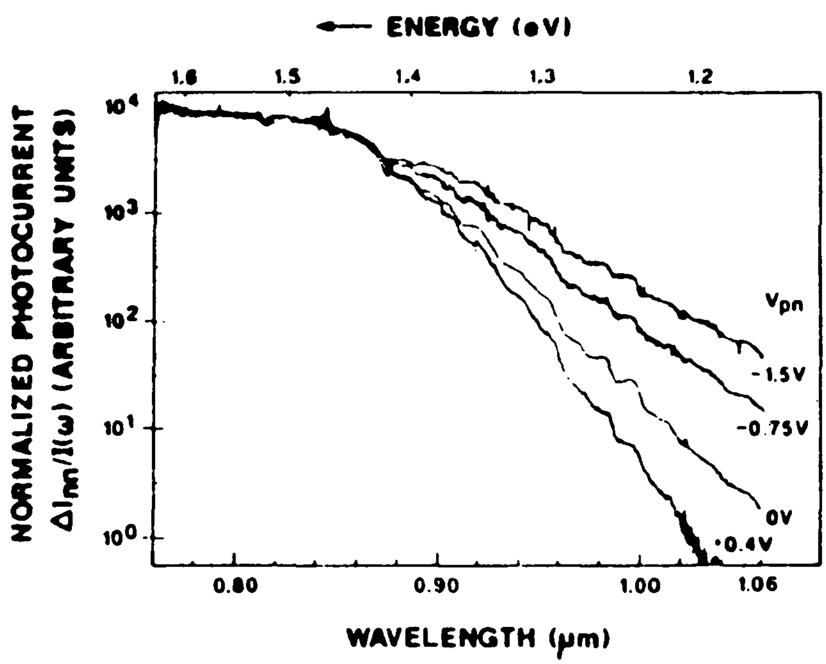
BANDPROFILE OF n-i-p-i CRYSTAL



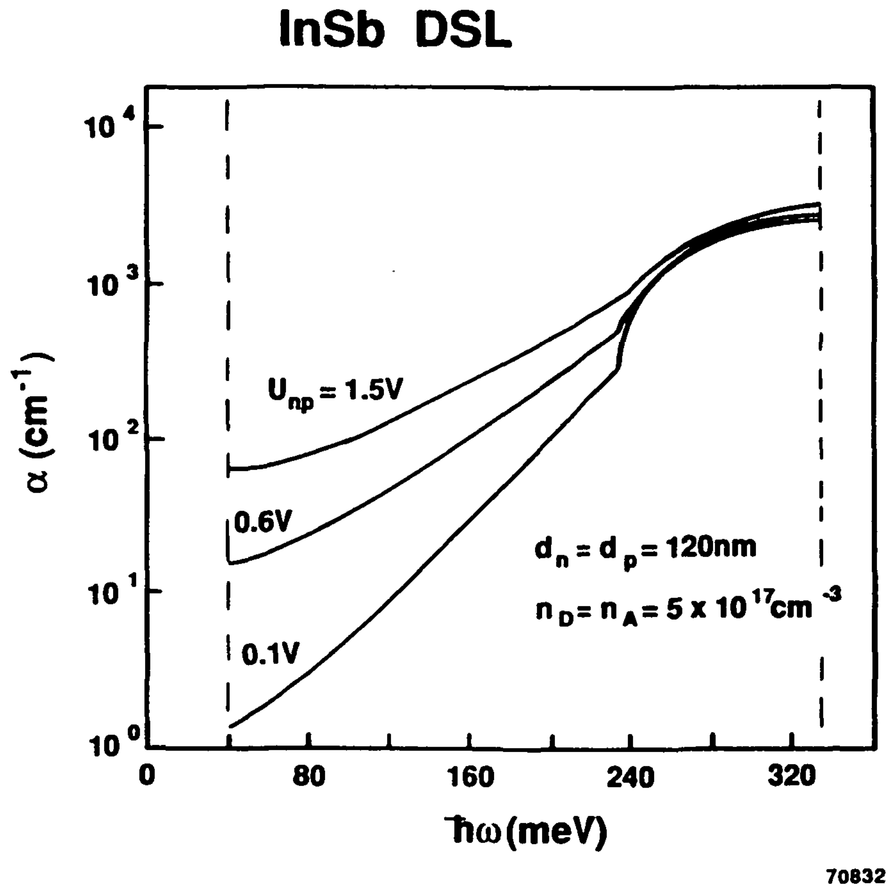
a) Ground State

b) Reverse Bias U_{np}

c) Forward Bias U_{np}



C.J. Chang-Hasnain, et al. (1986)



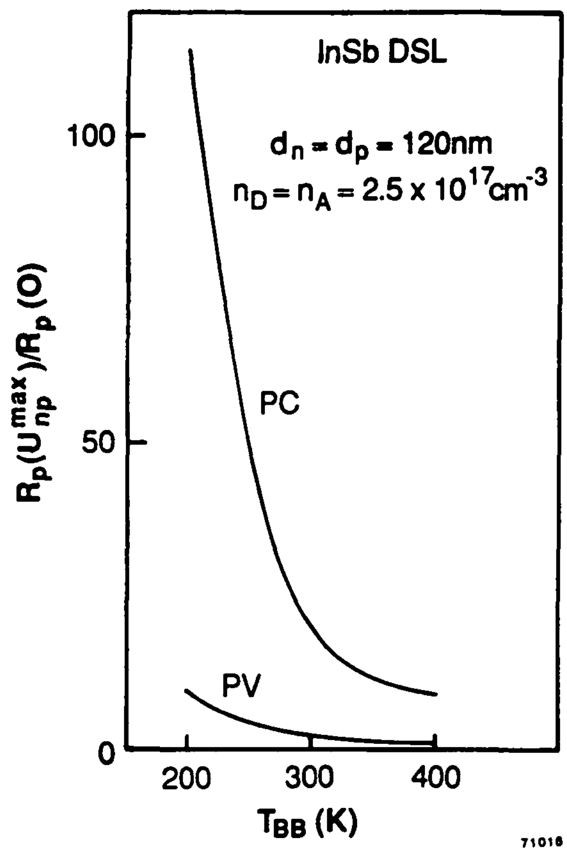
Spectrally Agile nipi Detector

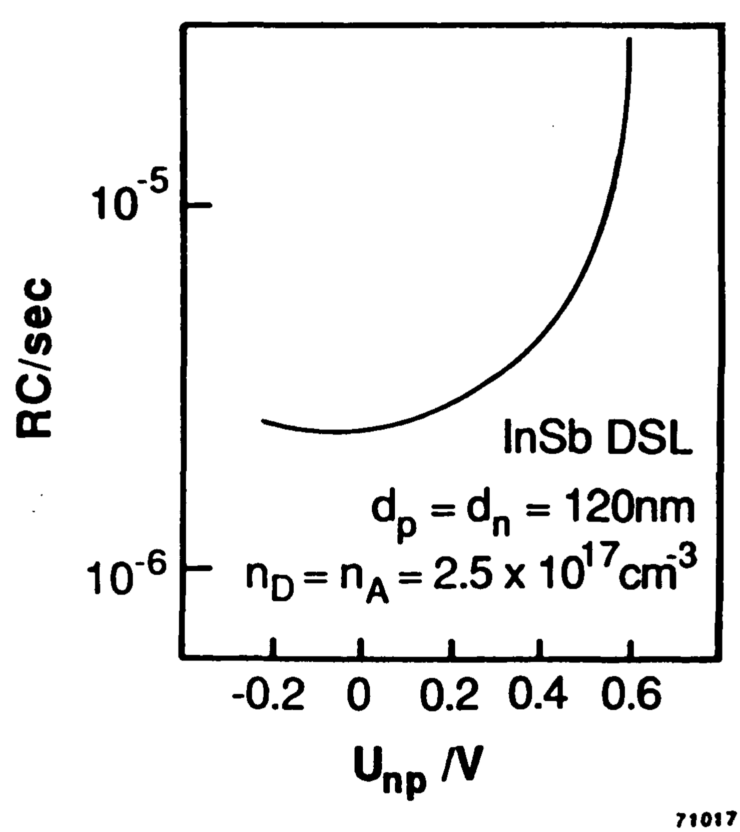
incident spectrum: $\phi_o M_p(E,T_T)$

$$I_{ph}(U_{np}) = \frac{q\mu\tau(U_{np})V_a}{L}\ \phi_o \int dE\ \eta(U_{np},E)\ M_p(E,T_T)$$

$$= \frac{q\mu\tau(U_{np})Va}{L}\ \phi_o\bar{\eta}\ (U_{np},T_T)$$

$$\frac{I_{ph}(U_{np1})}{I_{ph}(U_{np2})} = \frac{\tau(U_{np1})}{\tau(U_{np2})}\ \frac{\bar{\eta}(U_{np1},T_T)}{\bar{\eta}(U_{np2},T_T)} \quad \rightarrow \quad T_T$$

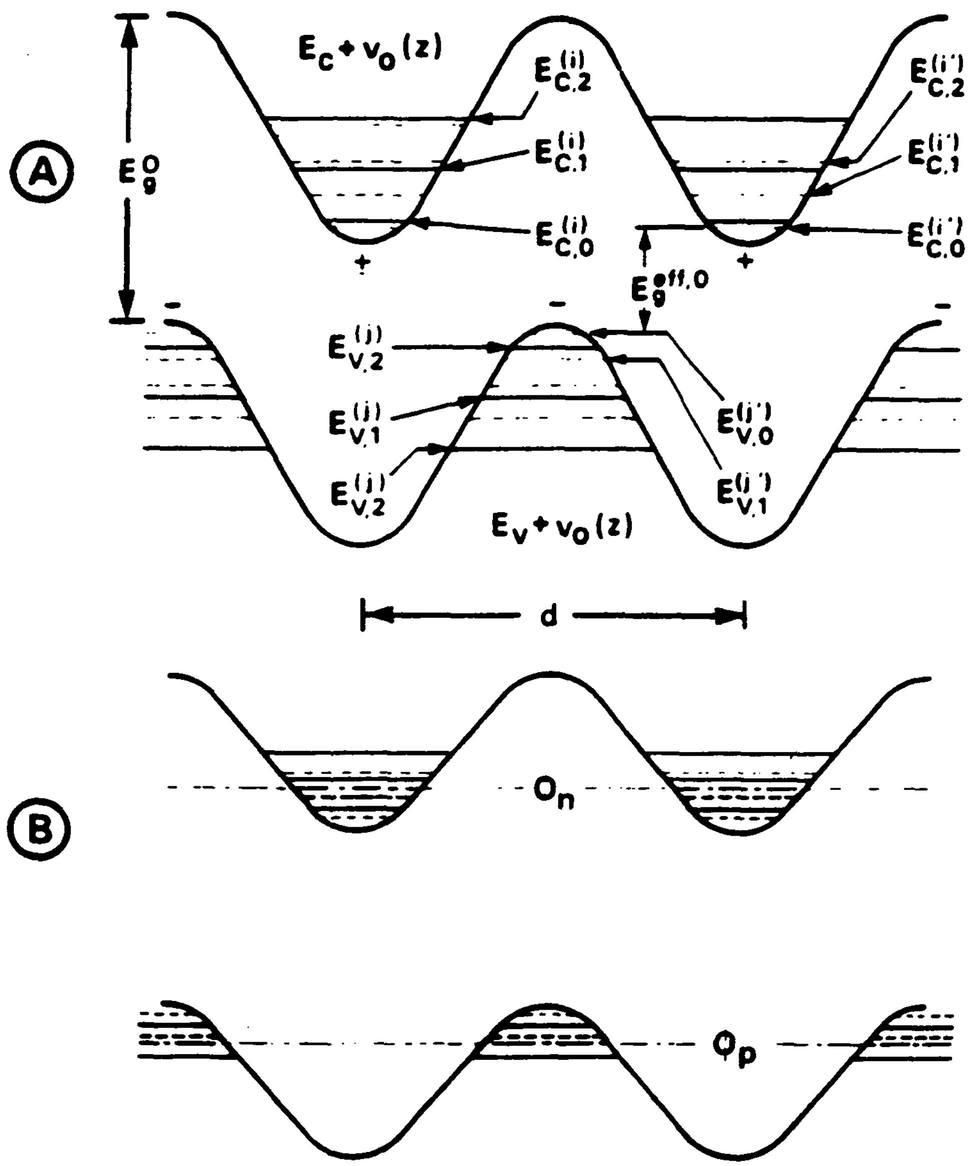

InSb DSL
$d_n = d_p = 120nm$
$n_D = n_A = 2.5 \times 10^{17} cm^{-3}$
100
50
0
$R_p(U_{np}^{max})/R_p(O)$
PC
PV
200
300
400
T_{BB} (K)
71016


10^{-5}
10^{-6}
RC/sec
InSb DSL
$d_p = d_n = 120nm$
$n_D = n_A = 2.5 \times 10^{17} cm^{-3}$
-0.2
0
0.2
0.4
0.6
U_{np} /V
71017

Schematic Band Diagram
for Doping Superlattice

A: Ground state

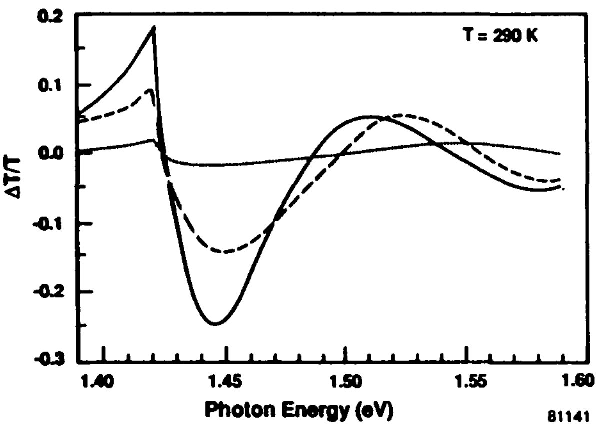
B: Excited state



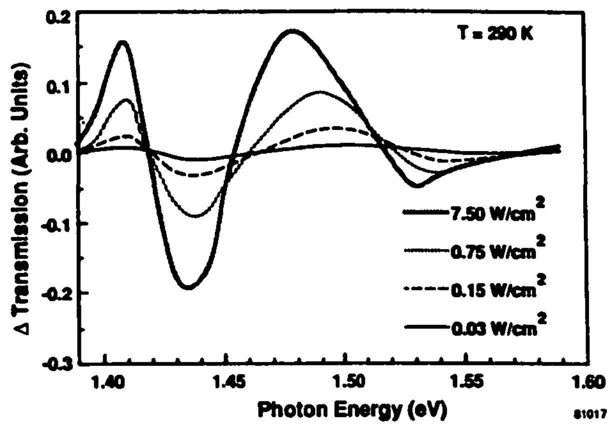
DIRECTION OF PERIODICITY z

Comparison of Theoretical and Experimental Results for Doping SL Transmission Nonlinearity

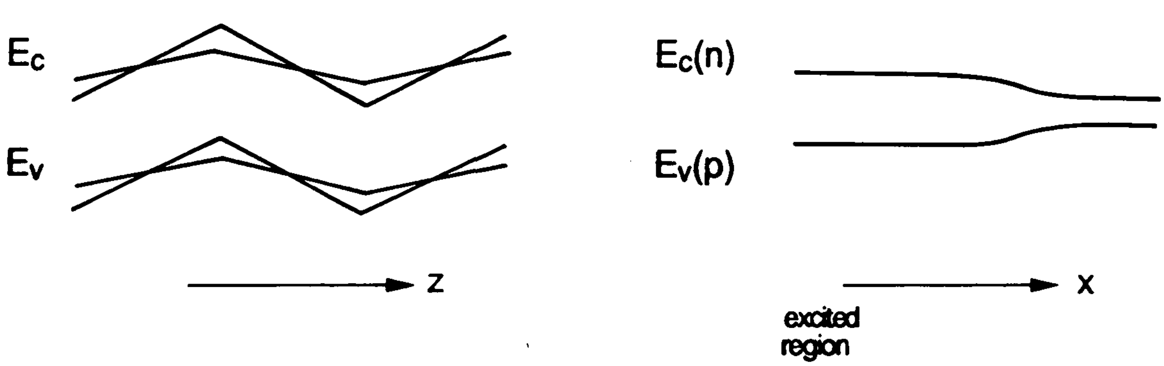
Theoretical Calculation of Optically Modulated Transmission
(GaAs Doping SL for Different Excitation Levels)



Optically Modulated Transmission
(GaAs Doping SL for Different Excitation Levels)



Lateral Charge Carrier Distribution

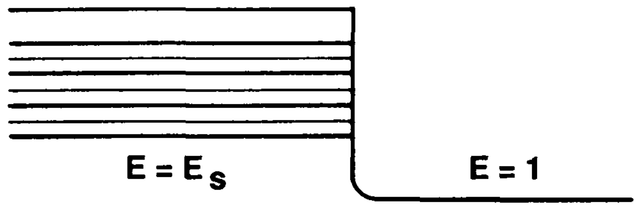


$$j_n \ \alpha \ [(V(n^{(2)})-V_o)+kT]\,(dn^{(2)}/dx)$$

$$R(n^{(2)}) \ \alpha \ n^{(2)}p^{(2)} \exp(-V(n^{(2)})/kT)$$

$$n^{(2)}(x) \approx n_o^{(2)} \exp(-x/L(n^{(2)}))$$

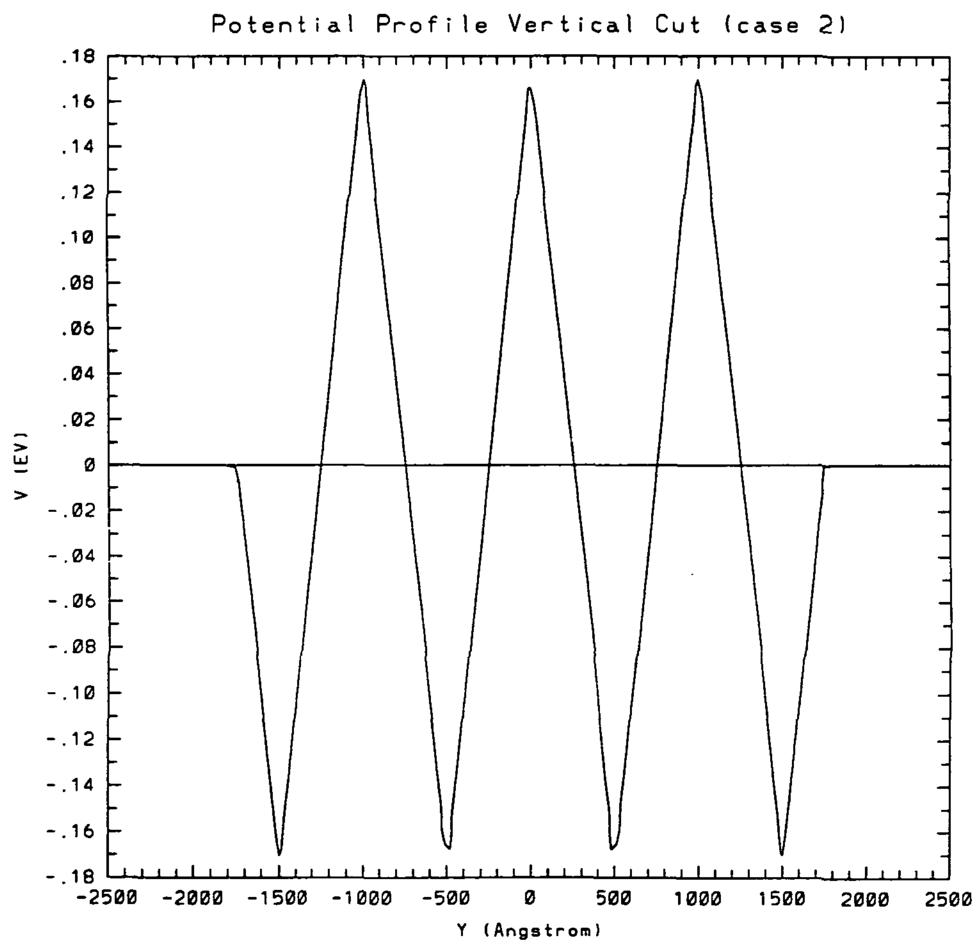
Potential At Surface

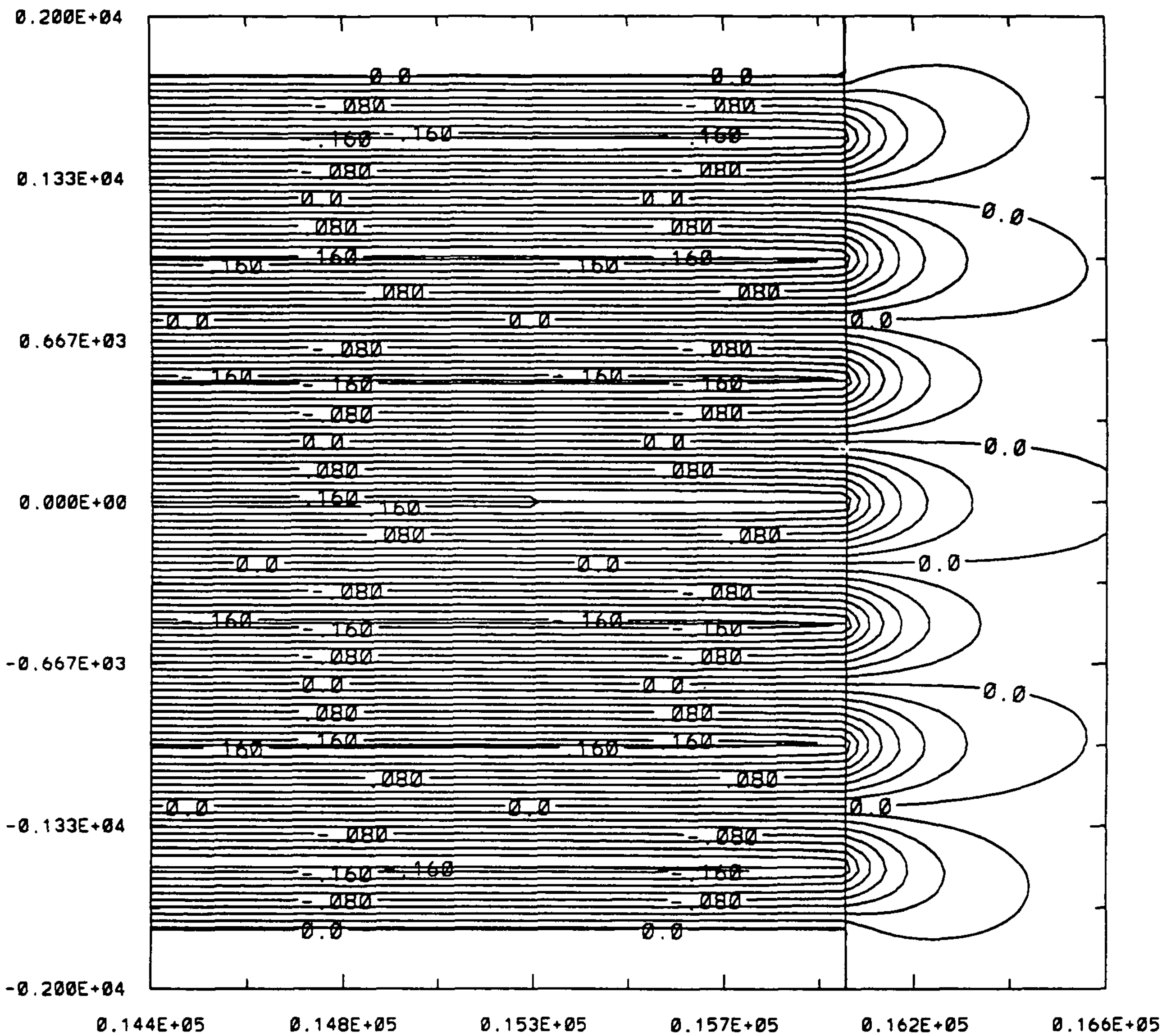


Surface Recombination May Reduce Effective Lifetime
→ Reduce Photoconductive Gain

Surface Potential Barrier

$$\sigma V_s \sim \frac{2V_o}{2E_s}$$





CONTOUR FROM -0.16000 TO 0.16000 CONTOUR INTERVAL OF 0.20000E-01 PT(3,3)= 0.49929E-03

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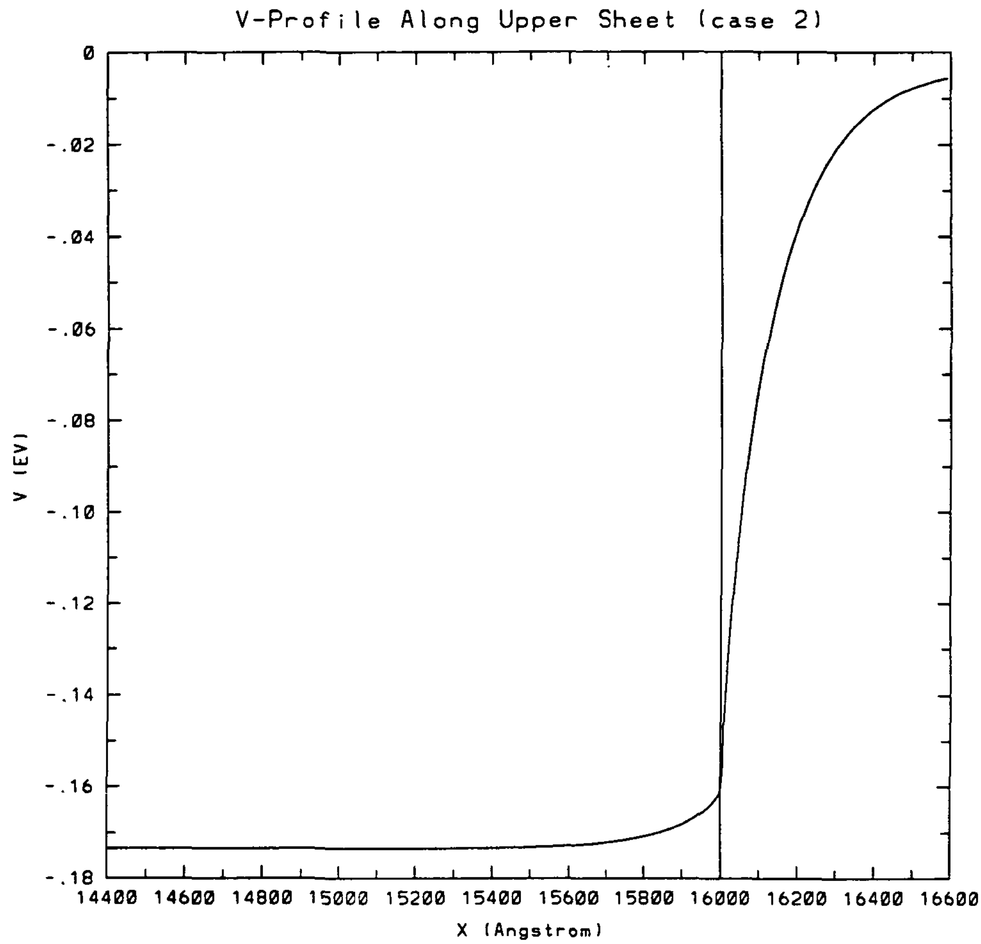

Summary

- IR detection with nipi SL based on InAs or InSb is feasible.
- Detector performance can be competitive.
- Spectrally agile detectors may be practical.
- Non-uniform excitation, su face and contact effects are critical.
- Optical nonlinearity can be useful.