InAs/(GaIn)Sb Short Period Superlattices for IR Detection

F. Fuchs, L. Bürkle, R. Hamid, N. Herres, W. Pletschen, R. E. Sah, R. Kiefer, and J. Schmitz

Fraunhofer-Institut für Angewandte Festkörperphysik (IAF)
Freiburg, Germany

Fraunhofer Institut Angewandte Festkörperphysik

Outline

- Introduction
- MBE growth and characterization
- Assessment of transport properties
- Diode performance
- Wannier Stark Localization

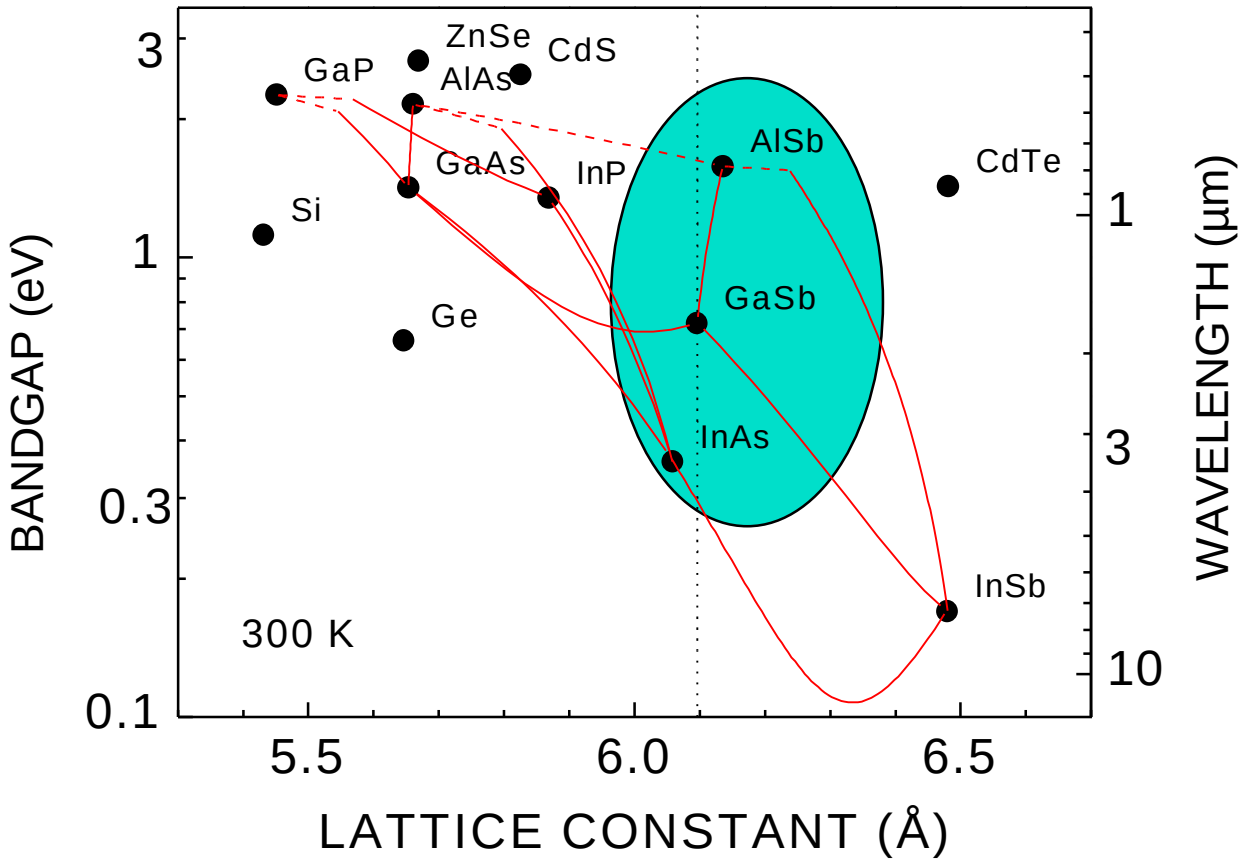
IAF
Fraunhofer Institut
Angewandte
Festkörperphysik

InAs/(Ga In)Sb Superlattices for IR Devices:

- High responsivity at normal incidence: Short integration times
- Bandgap tunable in the complete MIR (3 - 20 µm)
- Photovoltaic detection mode
- Reduced Auger recombination: High temperature Operation
- III-V Processing

IAF
Fraunhofer Institut
Angewandte
Festkörperphysik

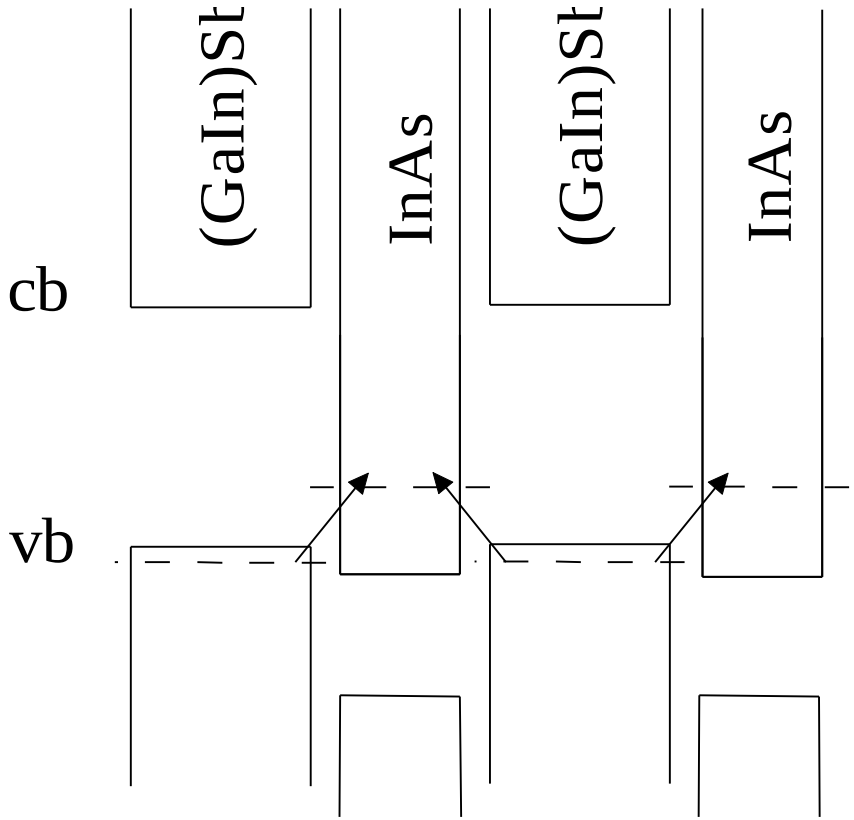
The InAs/GaSb/AlSb Materials Family



IAF
Fraunhofer Institut
Angewandte
Festkörperphysik

Band alignment of InAs/(GaIn)Sb superlattices

- Broken gap type IB
- $0 < E_g < 0.4$ eV
  ($20\ \mu m < \lambda < 3\ \mu m$)



IAF
Fraunhofer Institut
Angewandte
Festkörperphysik

MBE growth conditions

V/III BEP ratios:

Sb/(Ga + In) :	2 - 4.5
As/In:	5 -8
Growth temperatures:	360 °C - 440 °C
Growth rates:	(Ga In)Sb 1.35 µm /h
	InAs 0.35 µm /h

a) Alternating Fs

Group III soaks corresponding to deposition of 1 ML

b) Mixed Fs

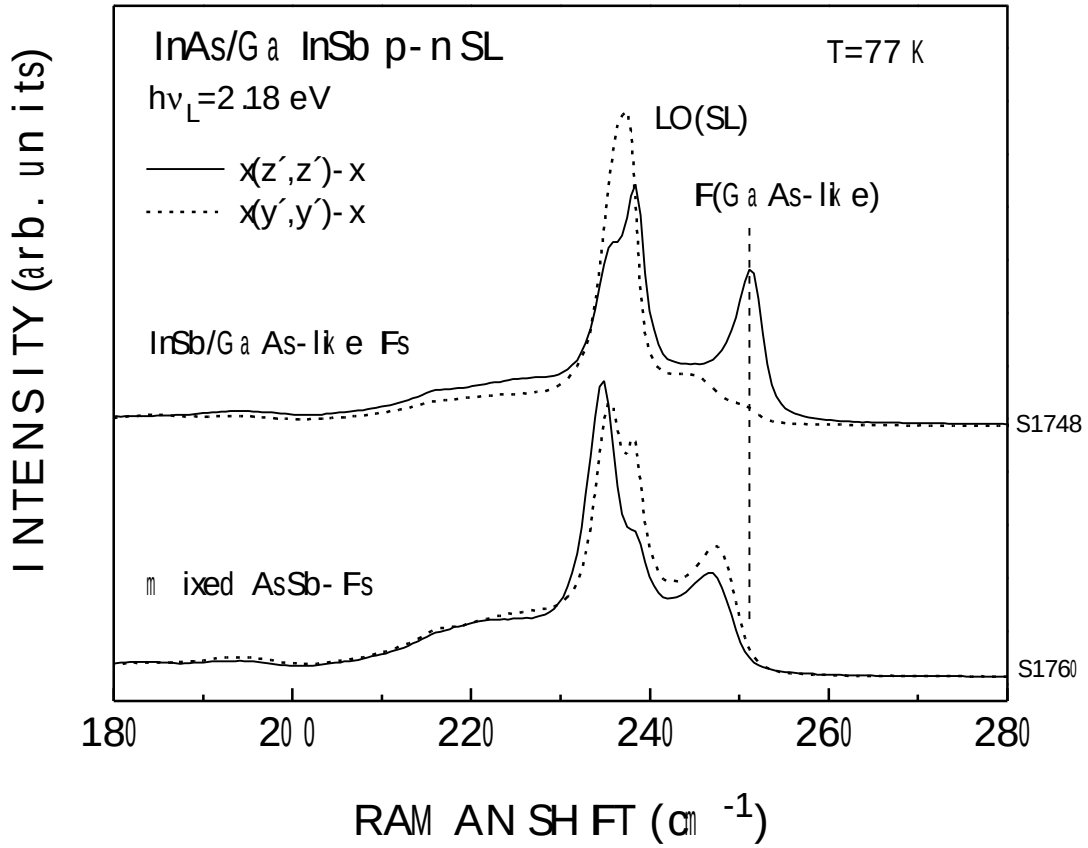
no group III soak

As valved cracker cell:	T_c = 800 °C
Sb valved cracker cell:	T_c = 800 °C

IAF

Fraunhofer Institut
Angewandte
Festkörperphysik

Raman: Alternating vs mixed interface



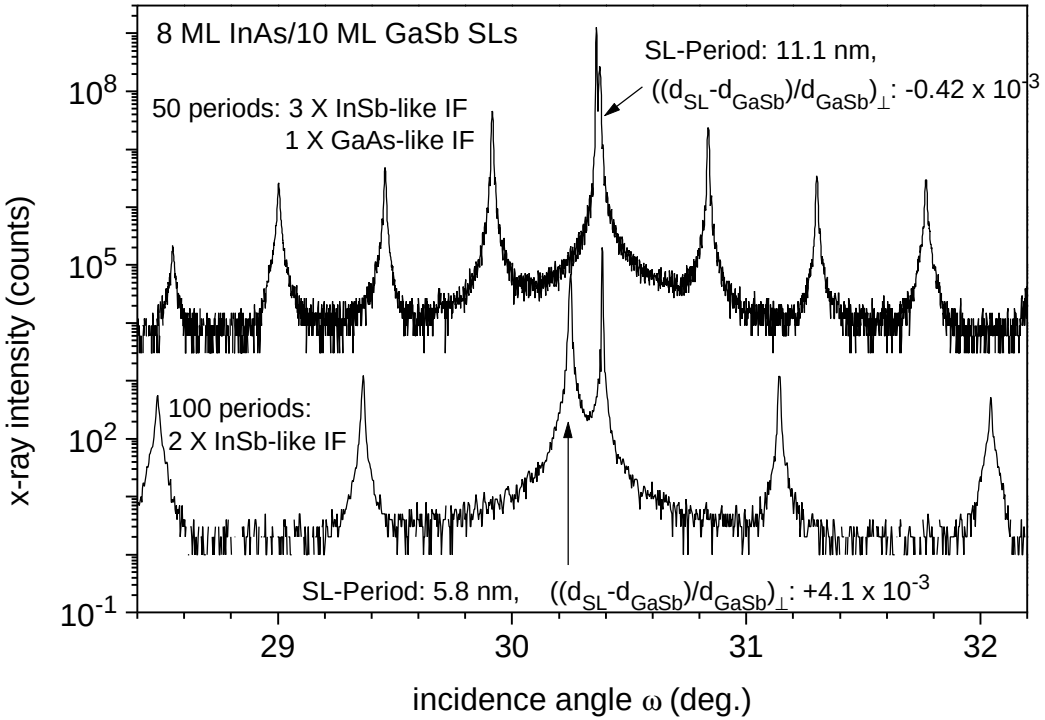
Fraunhofer Institut
Angewandte
Festkörperphysik

Strain adjustment by interface engineering

- Net strain
- SL period

⇒ 1 µm SL stack:

⇒ $\Delta a/a < 2 \times 10^{-3}$



Fraunhofer Institut Angewandte Festkörperphysik

High resolution X-ray diffraction

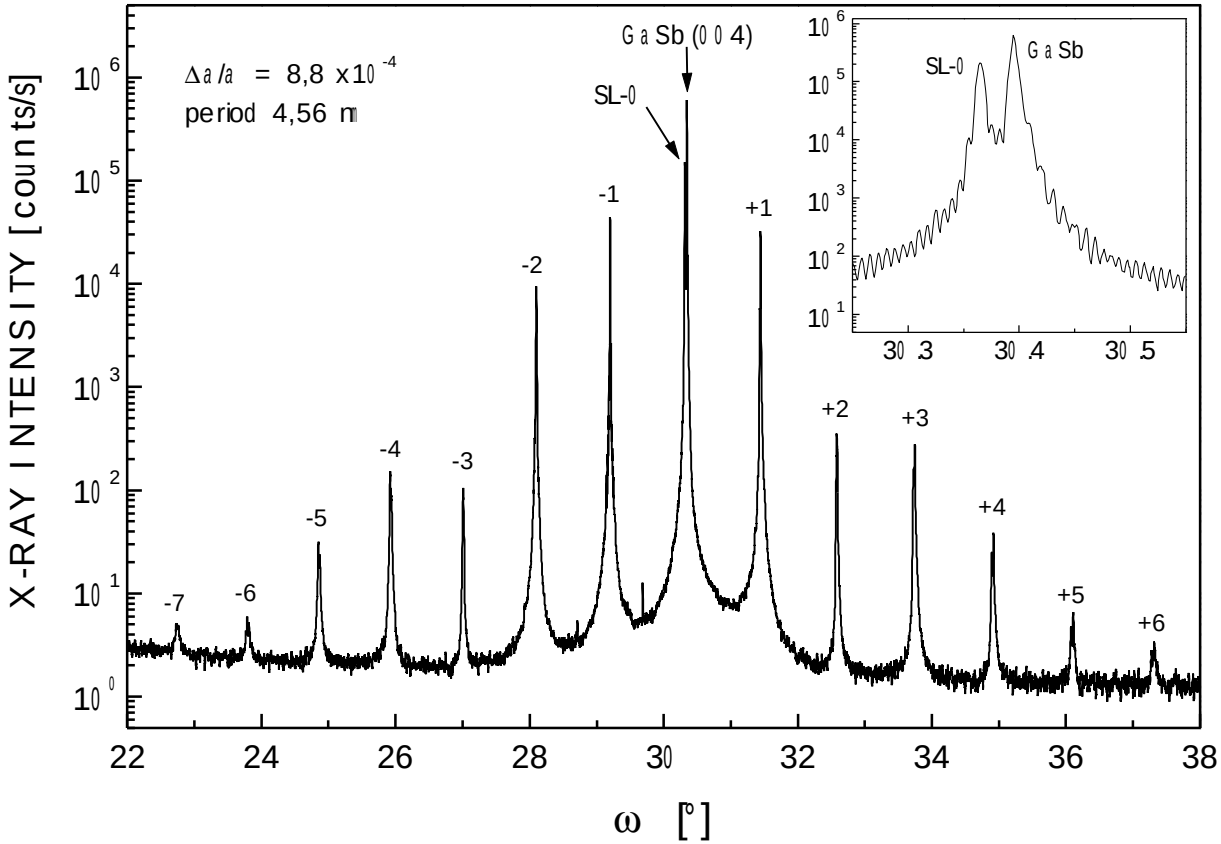
- Net strain
- SL period

⇒ 1 µm SL stack :

⇒ $\Delta a/a < 2 \times 10^{-3}$

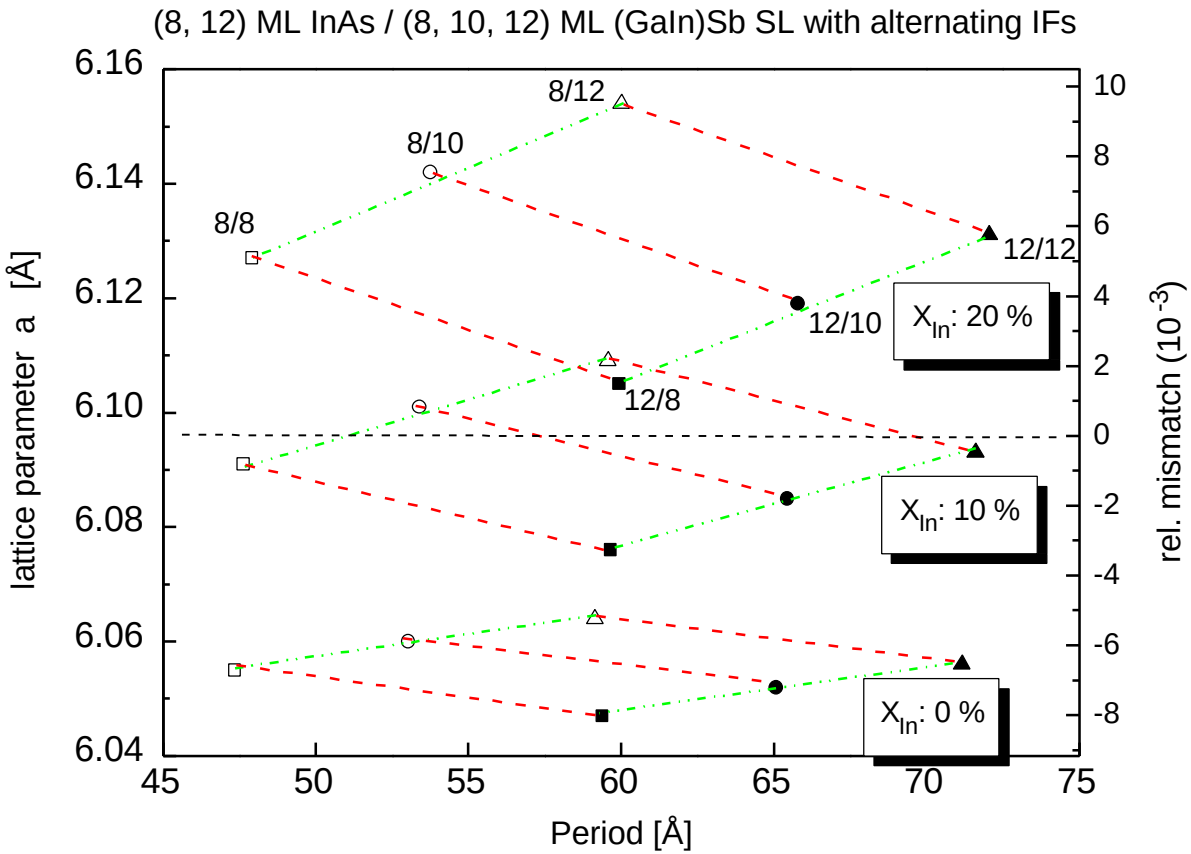
100 X

F: GaAs-like
8 ML $Ga_{0.85}In_{0.15}Sb$
F: InSb-like
8 ML InAs



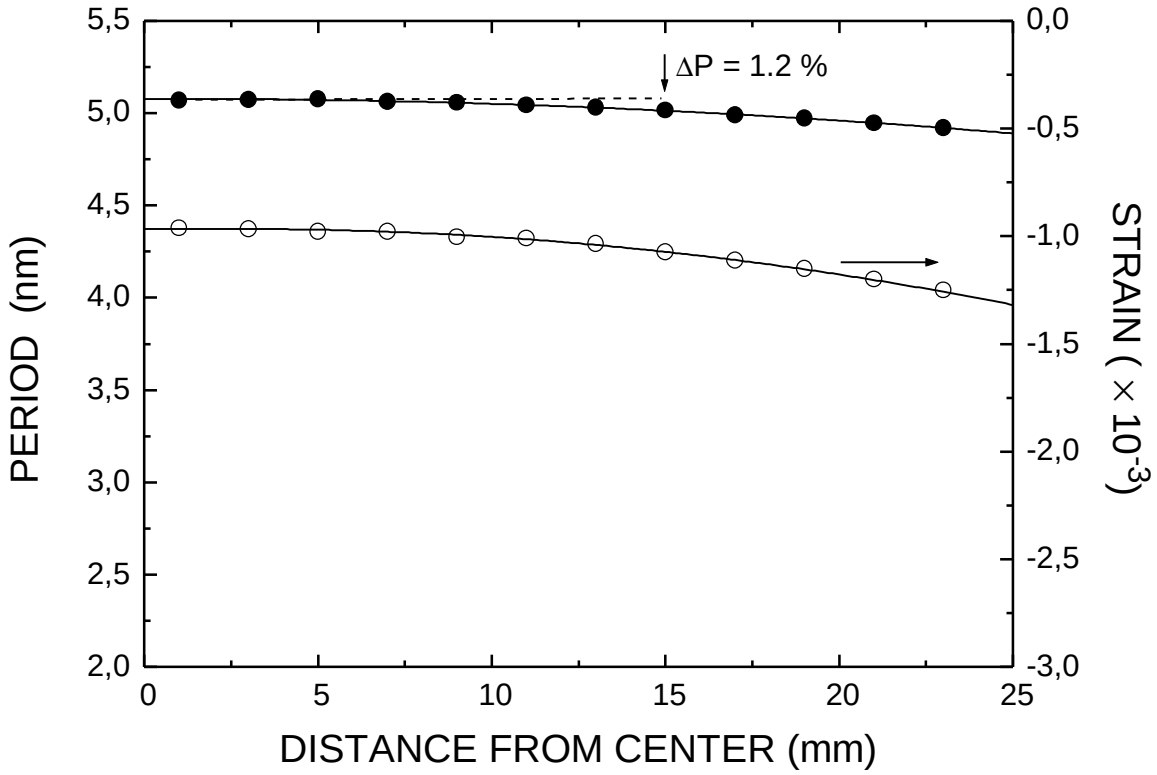
Fraunhofer Institut
Angewandte
Festkörperphysik

X-ray analysis



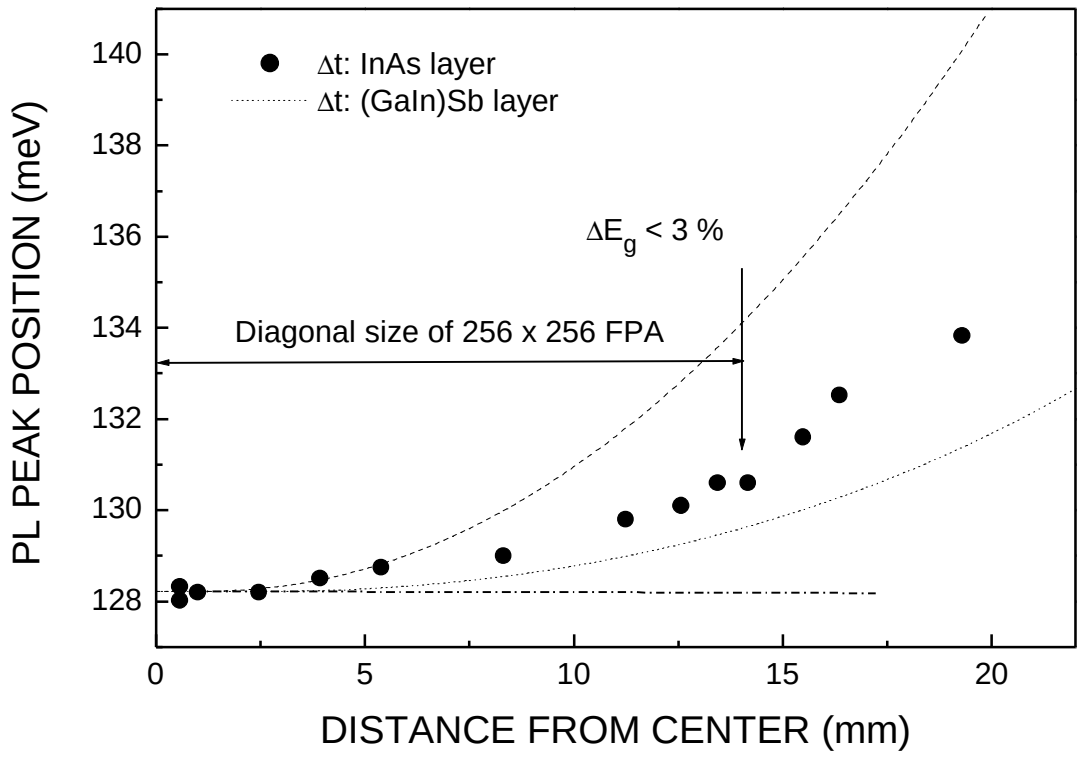
Fraunhofer Institut Angewandte Festkörperphysik

Homogeneity across a 2" wafer



IAF
Fraunhofer Institut
Angewandte
Festkörperphysik

Variation of the band gap



Fraunhofer Institut Angewandte Festkörperphysik

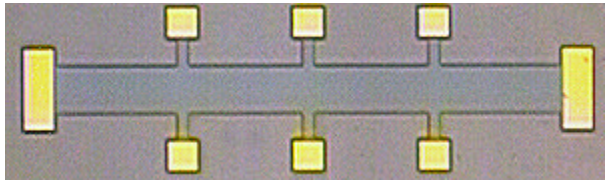
Asessment of the residual background

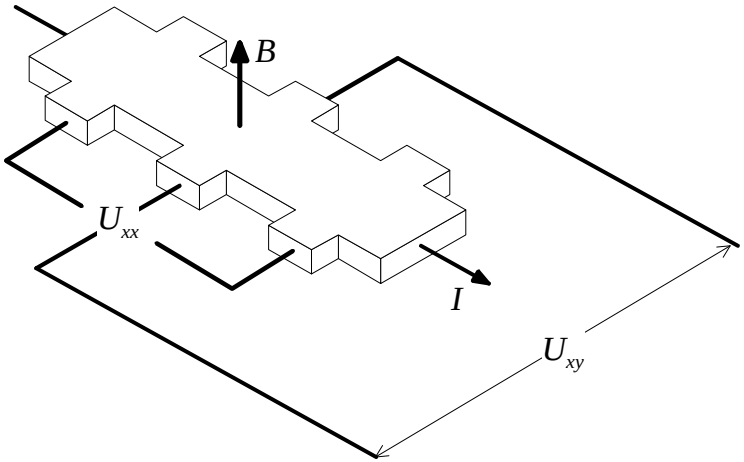
Fraunhofer Institut
Angewandte
Festkörperphysik

Magnetotransport

- Determination of carrier concentrations n_i and mobility m_i

$\Rightarrow$ background: $n < 1 \times 10^{16}\ cm^{-3}$





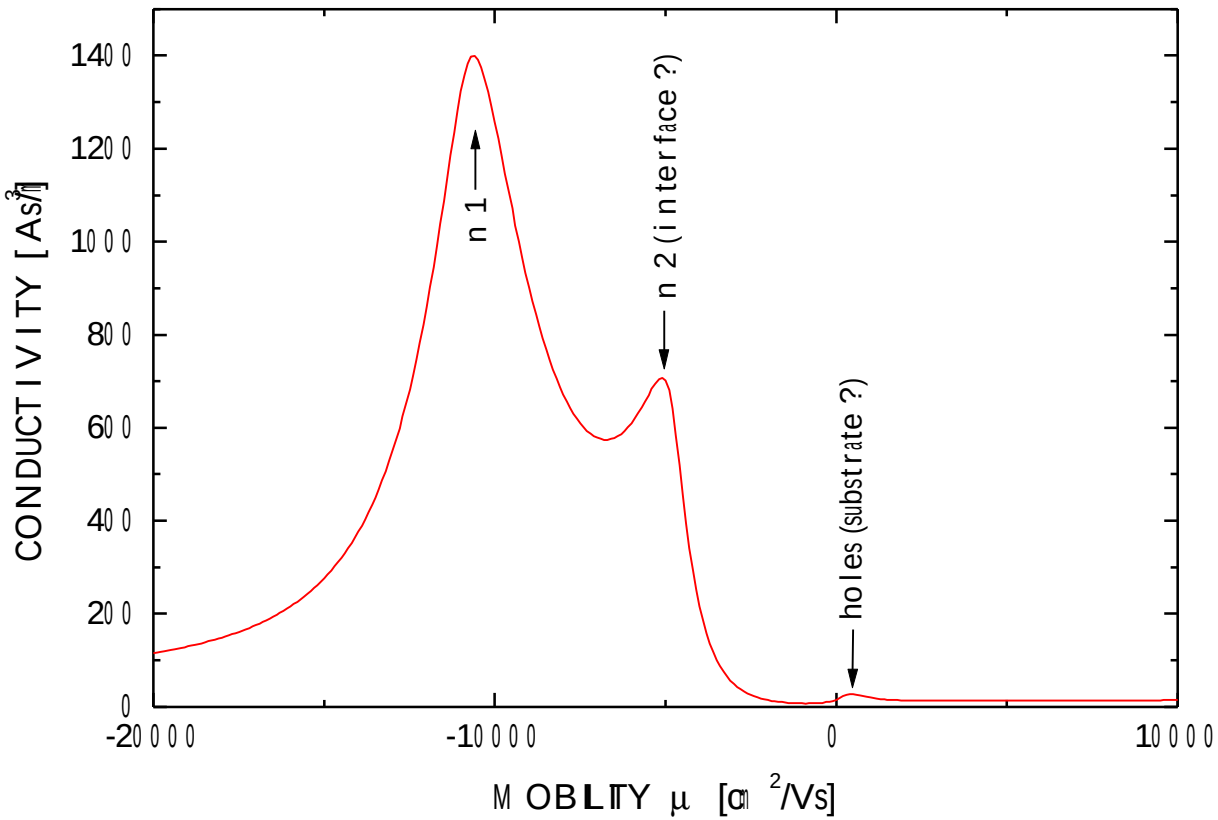
Fraunhofer Institut Angewandte Festkörperphysik

Mobility Spectrum Analysis (MSA)

- No assumptions necessary
- All contributing components become visible

$$s_{xx}(B) = \int_{-\infty}^{\infty} \frac{s(m)\,dm}{1+(mB)^2}$$

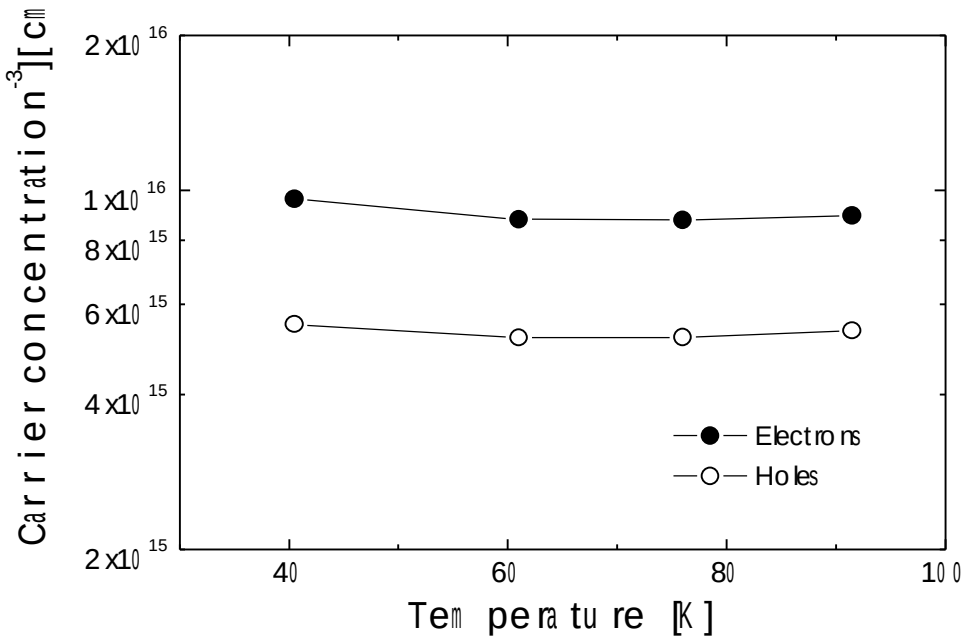
$$s_{xy}(B) = \int_{-\infty}^{\infty} \frac{s(m)mB\,dm}{1+(mB)^2}$$



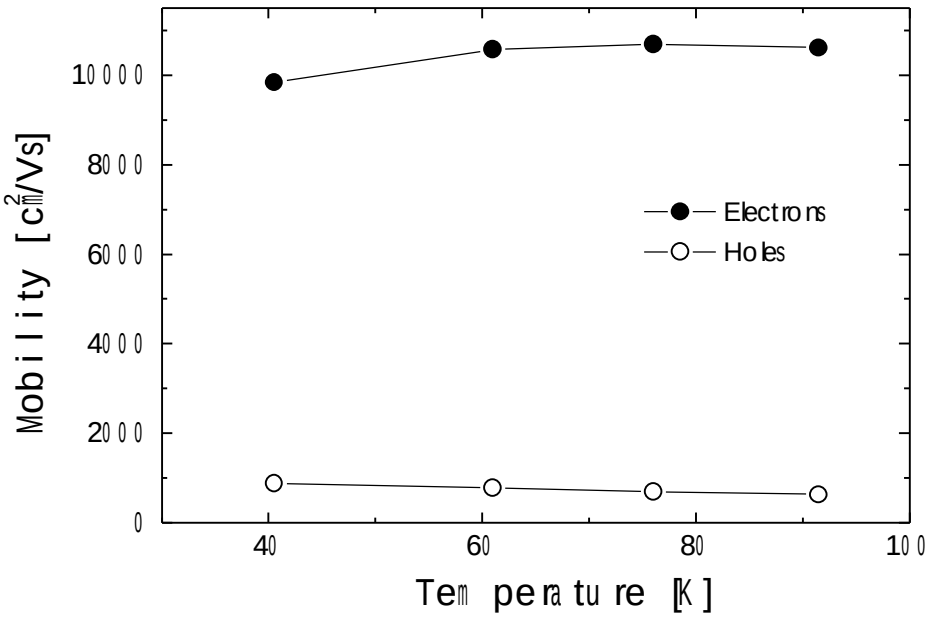
Fraunhofer Institut Angewandte Festkörperphysik

In-plane transport properties

Carrier concentration

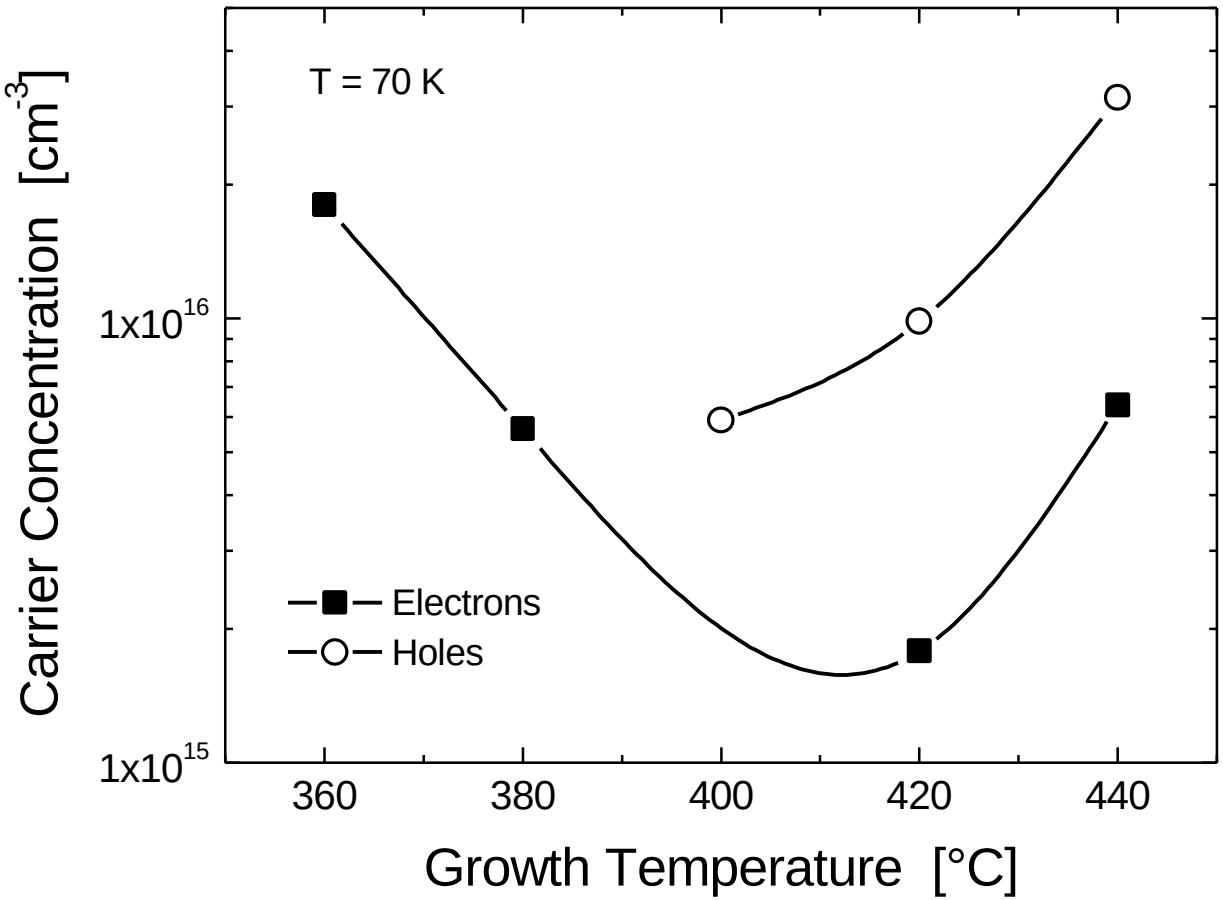


Mobility



IAF
Fraunhofer Institut
Angewandte
Festkörperphysik

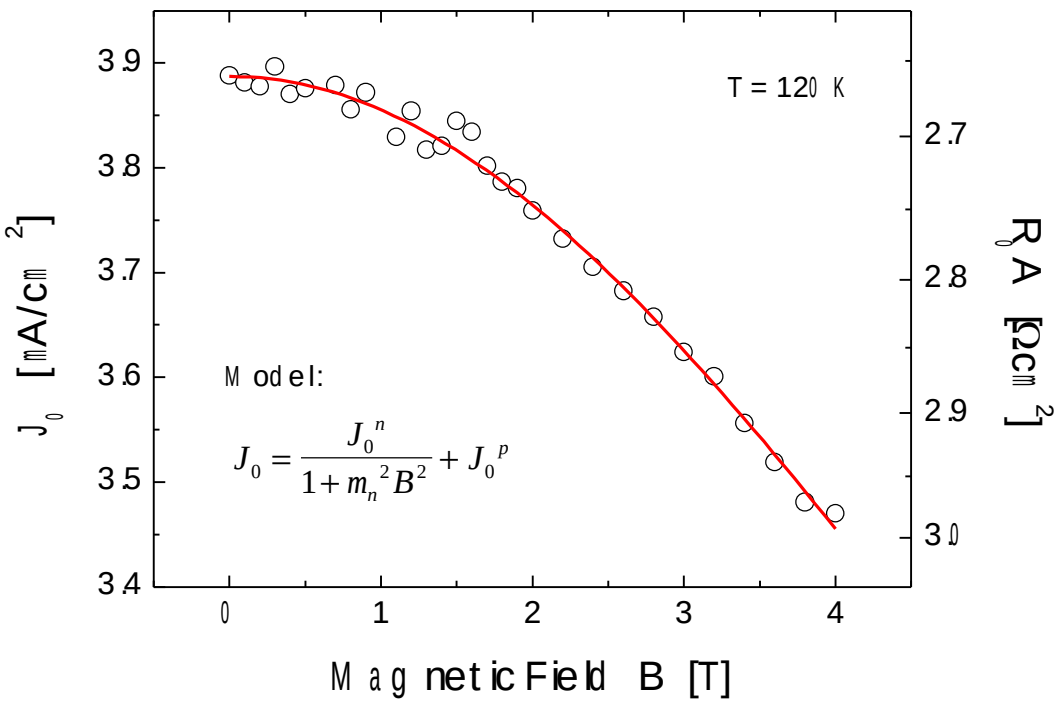
Residual Background Concentration



Bürkle, Fuchs, Schmitz, Pletschen,
Applied Physic Letters, Vol. 77, 1659 (2000)

IAF
Fraunhofer Institut
Angewandte
Festkörperphysik

Out-of-plane transport properties (results)



- Electron diffusion current makes up 70 % of total diode current
- Out-of-plane electron mobility μ_n = 1,200 cm²/Vs

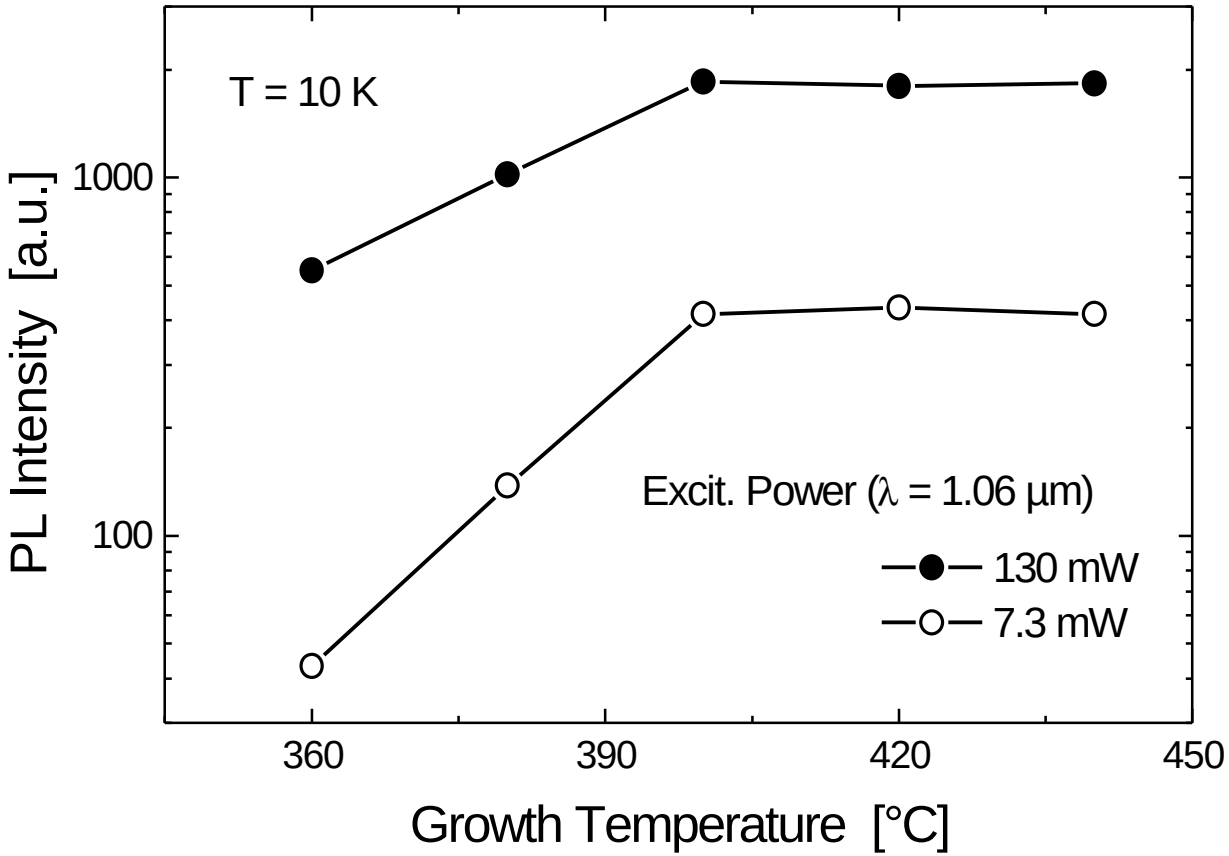
⇔ In-plane electron mobility μ_n = 10,000 cm²/Vs from Hall measurements

⇒ Reduction due to scattering at the SL interfaces

Fraunhofer Institut Angewandte Festkörperphysik

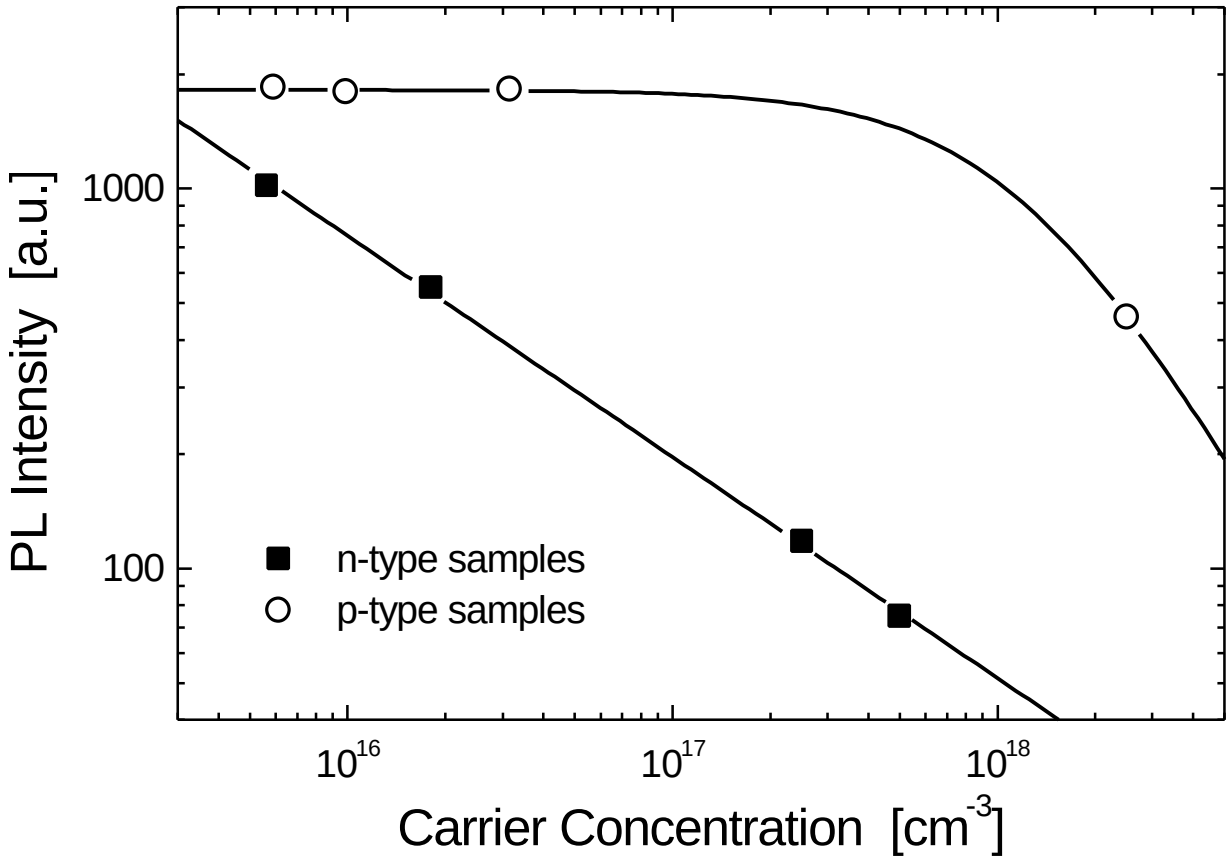
L. Bürkle, F. Fuchs, R. Kiefer, W. Pletschen, E. Sah, J. Schmitz
Mat. Res. Soc. Symp. Proc. Vol. 607, p.77 (2000)

PL intensity vs growth temperature



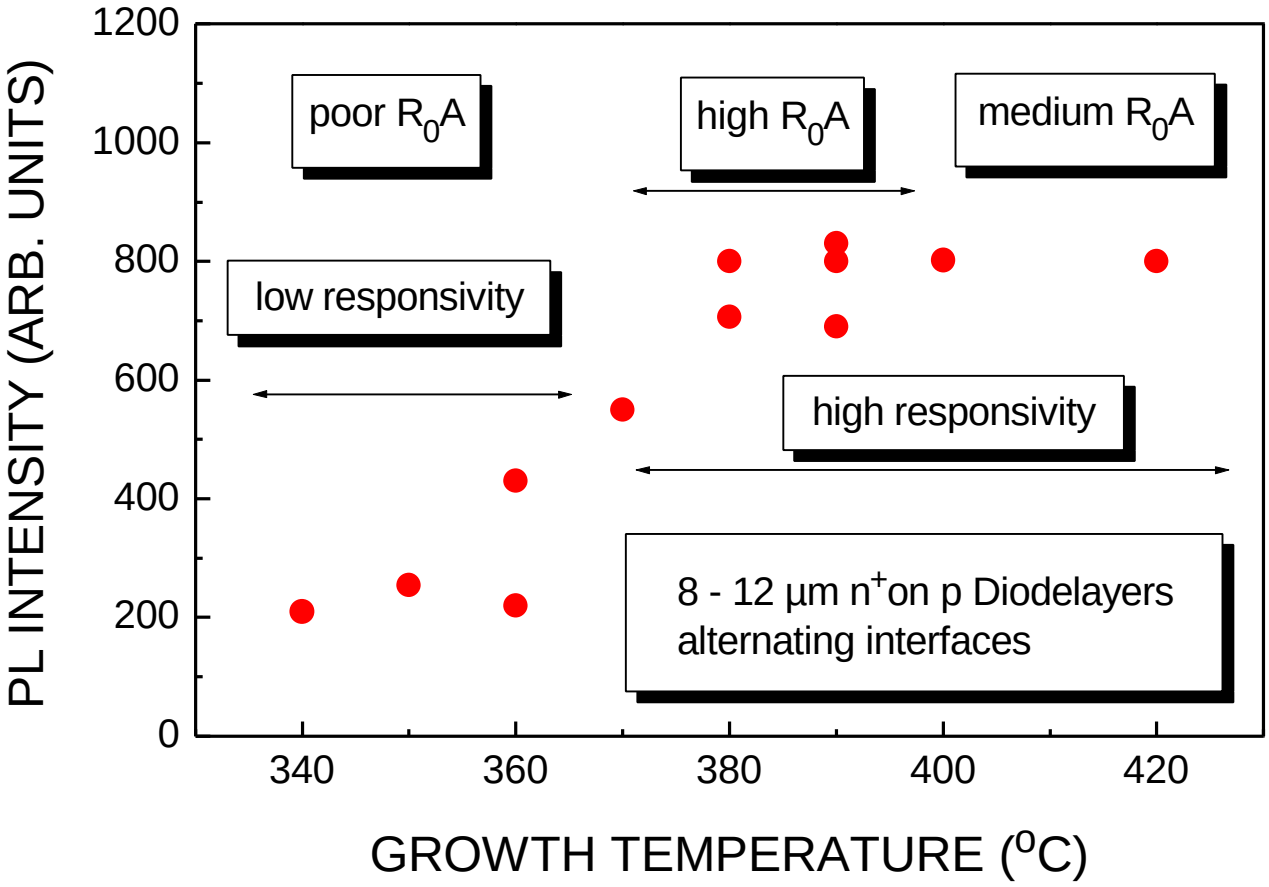
IAF
Fraunhofer Institut
Angewandte
Festkörperphysik

PL intensity vs carrier concentration



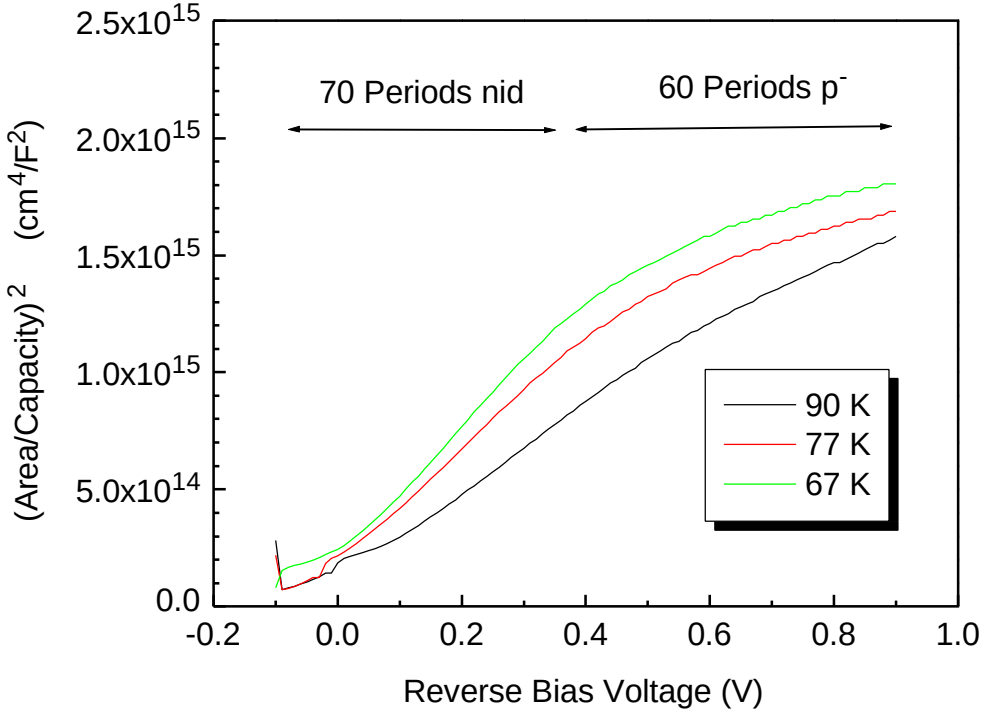
IAF
Fraunhofer Institut
Angewandte
Festkörperphysik

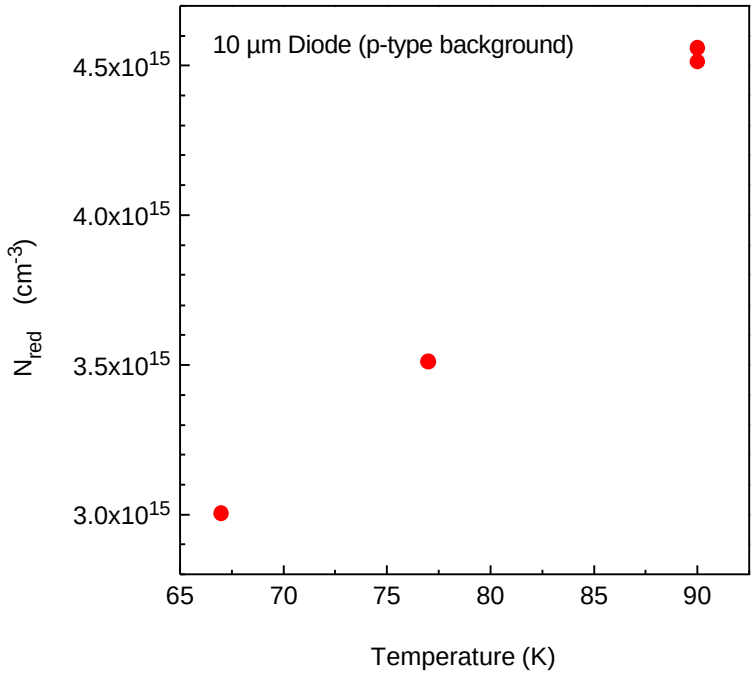
Korrelation PL vs Diode Performance



Fraunhofer Institut Angewandte Festkörperphysik

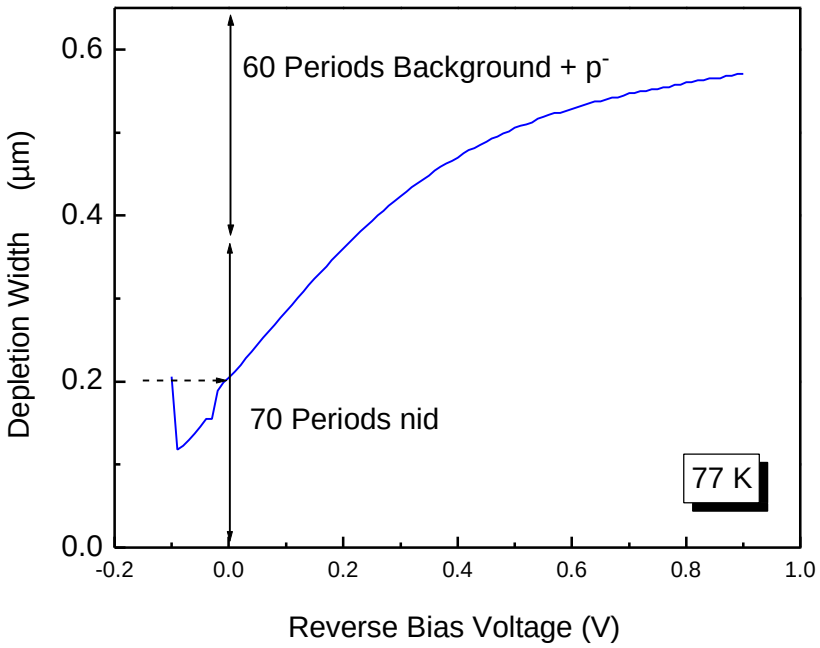
CV measurements (possible if $R_0A > 100\ \Omega cm^2$)

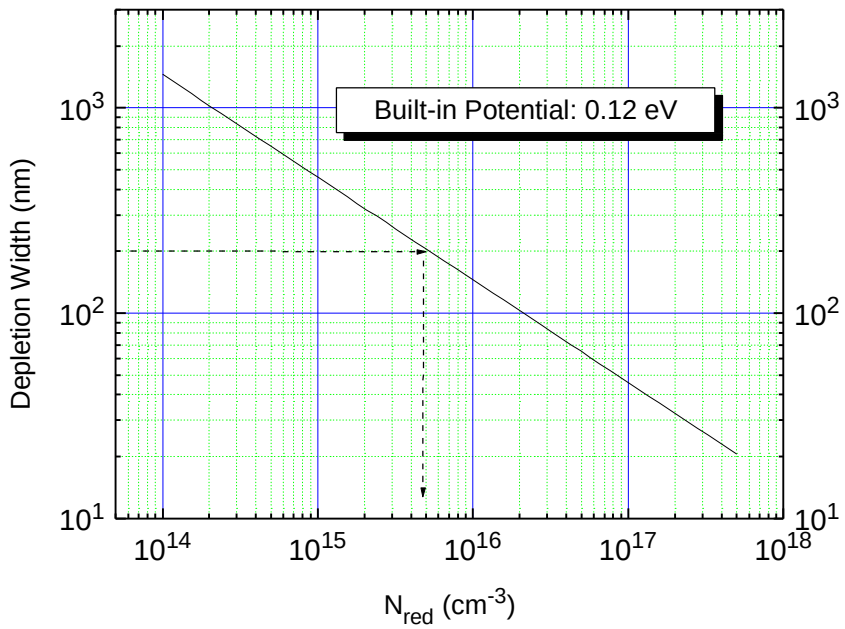




IAF
Fraunhofer Institut
Angewandte
Festkörperphysik

C-V measurements





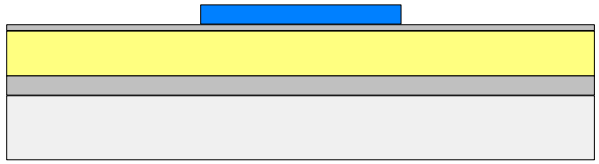
Fraunhofer Institut
Angewandte
Festkörperphysik

Diode performance

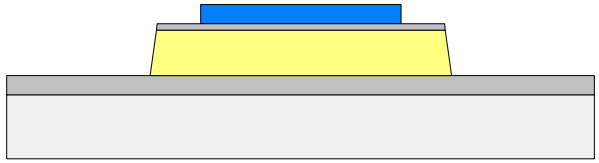
Fuchs, Bürkle, Hamid, Pletschen, Schmitz,
Proc. SPIE, 4288, p.171 (2001)

Processing

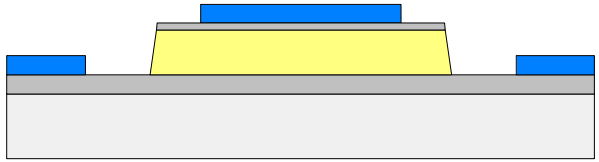
(a) Top Contact



(b) Definition of Mesa

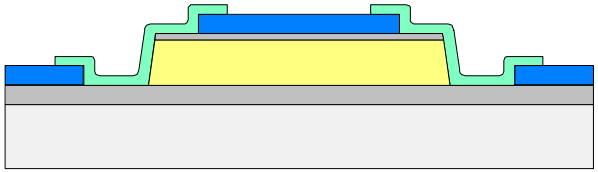


(c) Bottom Contact

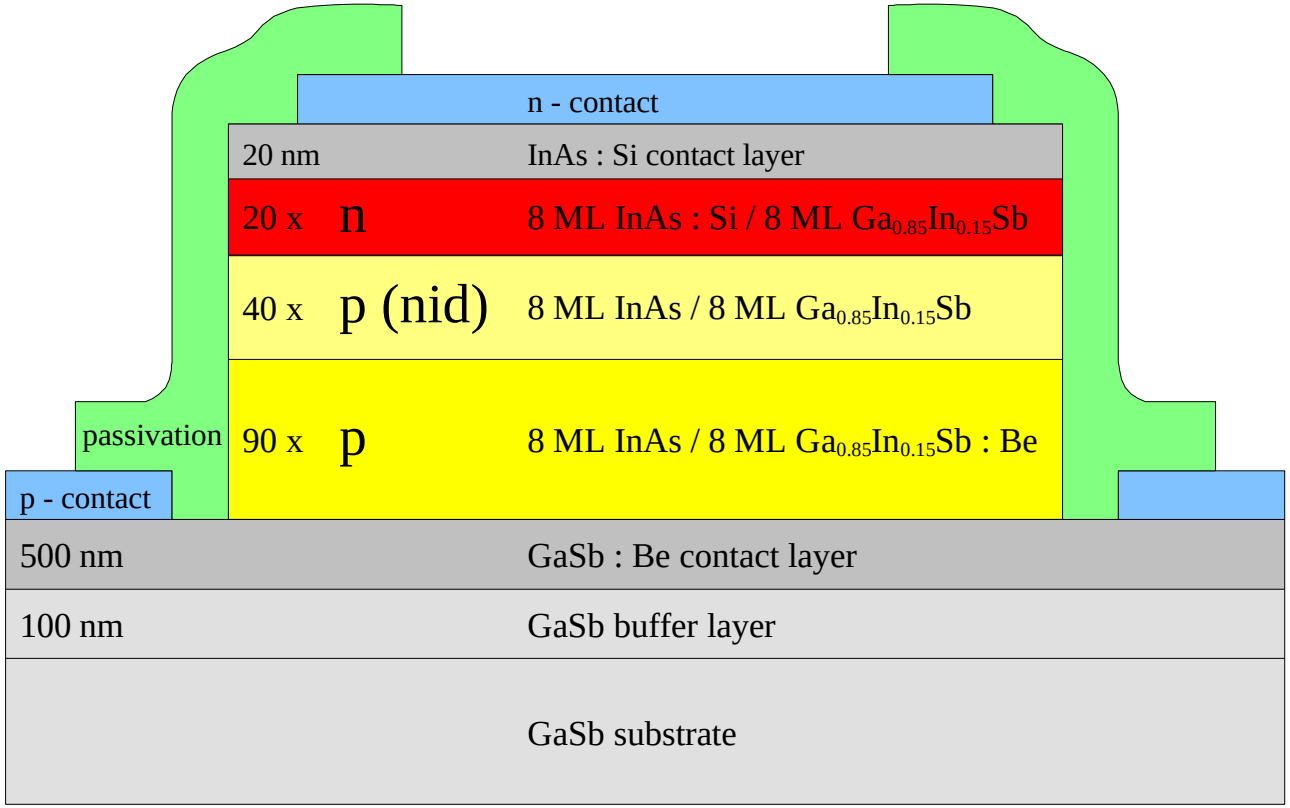


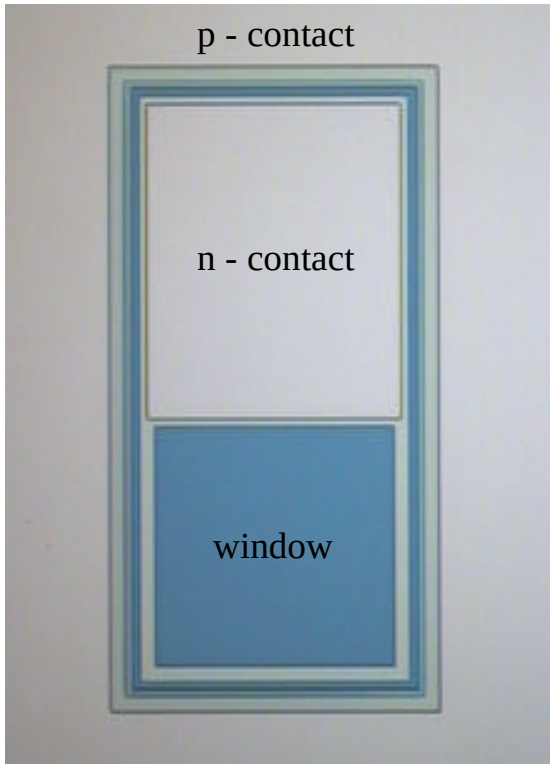
(d) Passivation

(e) Etching of Contact Holes

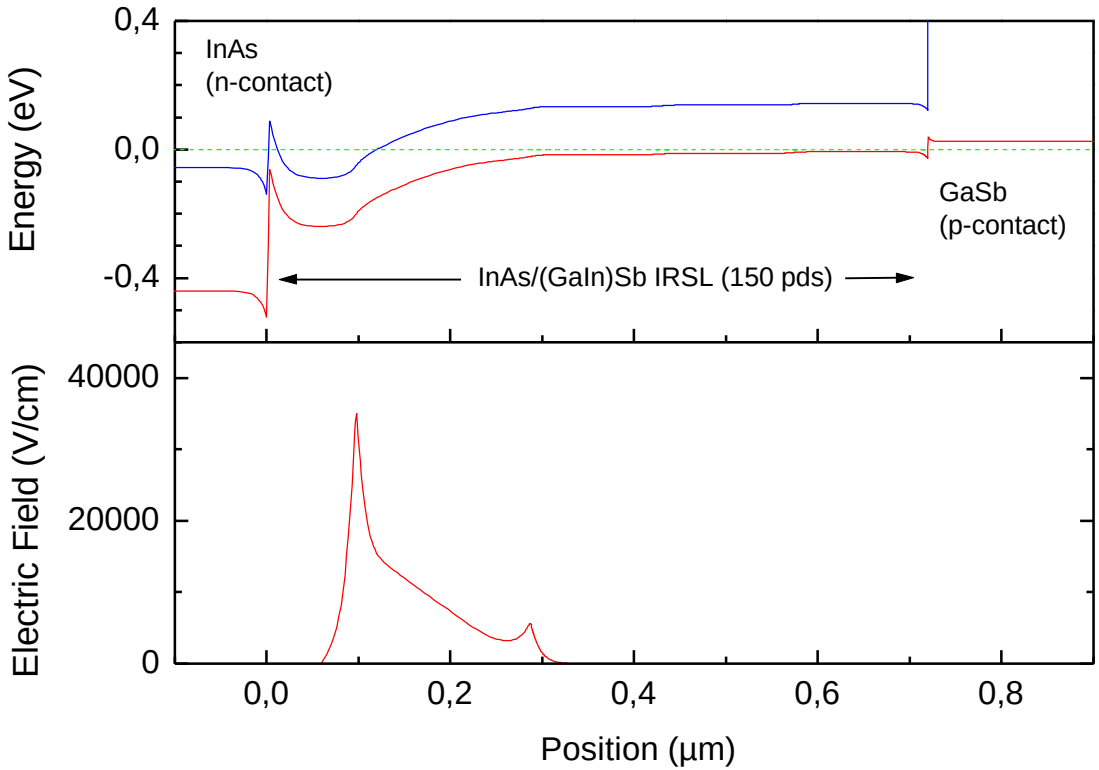


Characterization of InAs/GaInSb superlattice diodes



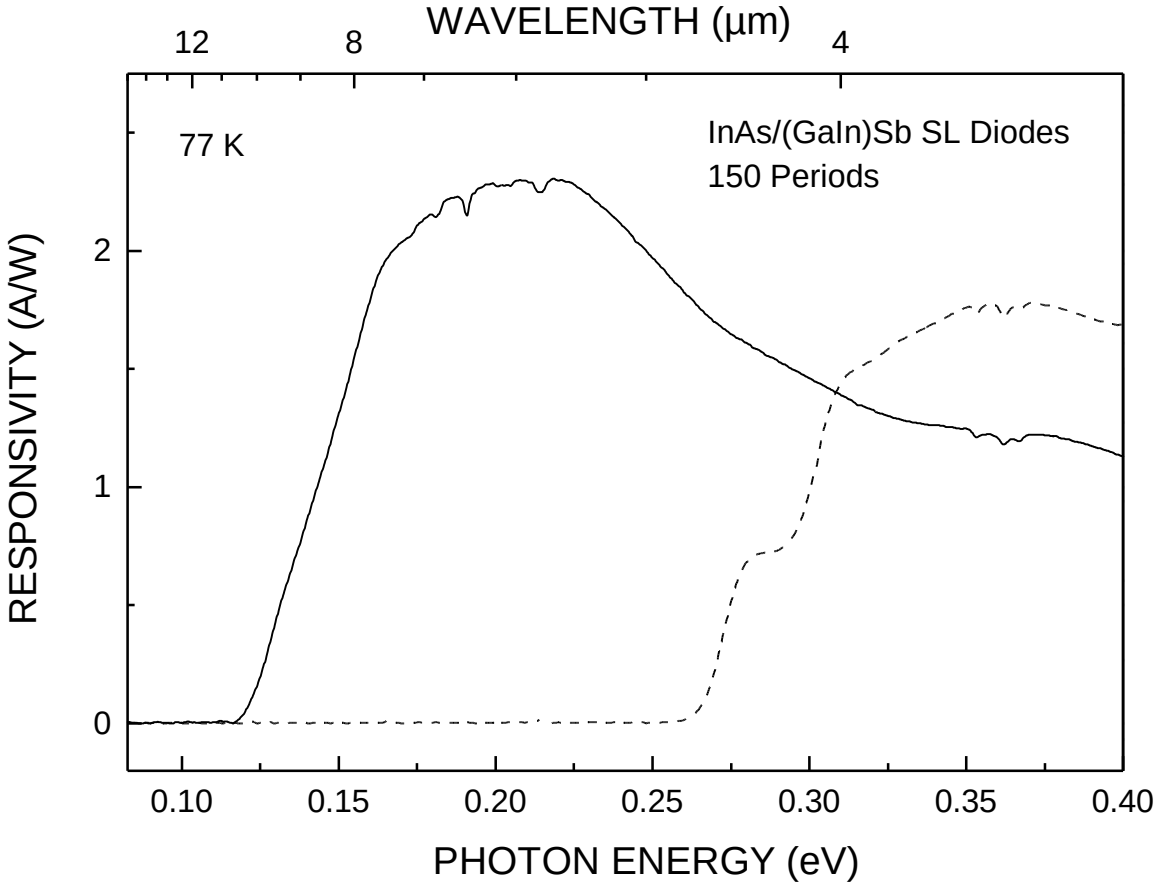


Effective band alignment of an InAs/(GaIn)Sb SL Diode



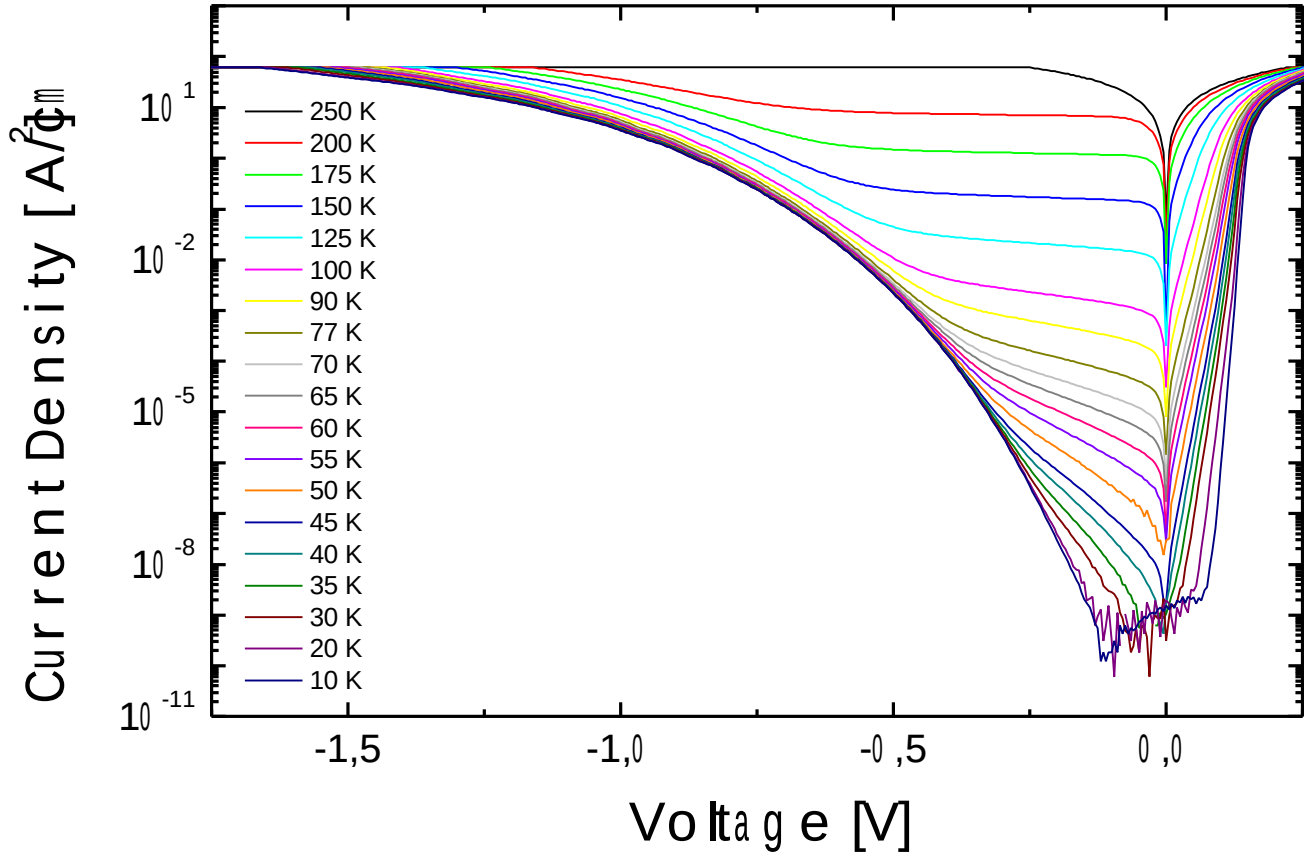
Fraunhofer Institut
Angewandte
Festkörperphysik

Responsivity of InAs/(GaIn)Sb SL Diodes (layer thickness 1 µm)



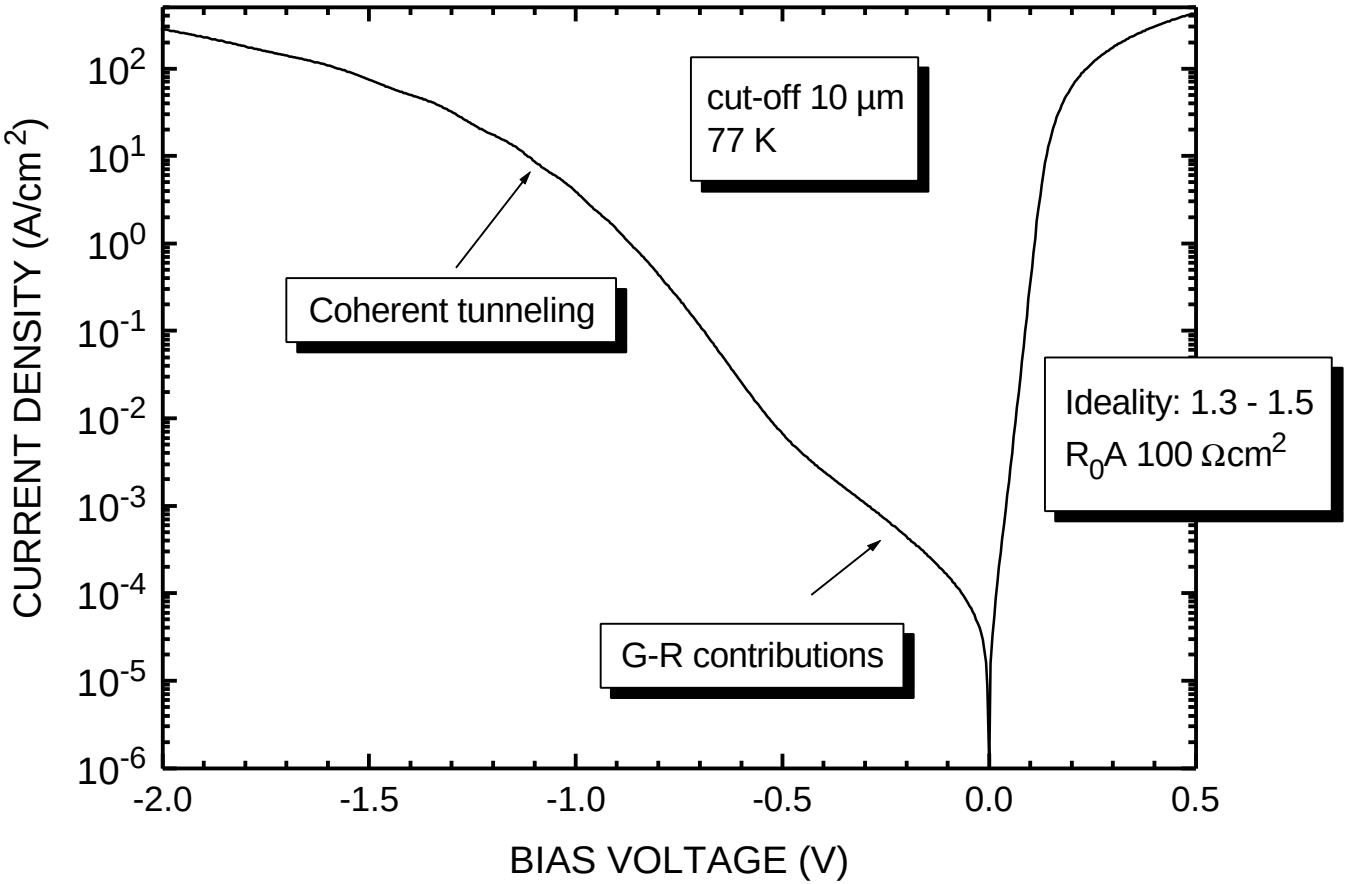
IAF
Fraunhofer Institut
Angewandte
Festkörperphysik

IV Characteristics



IAF
Fraunhofer Institut
Angewandte
Festkörperphysik

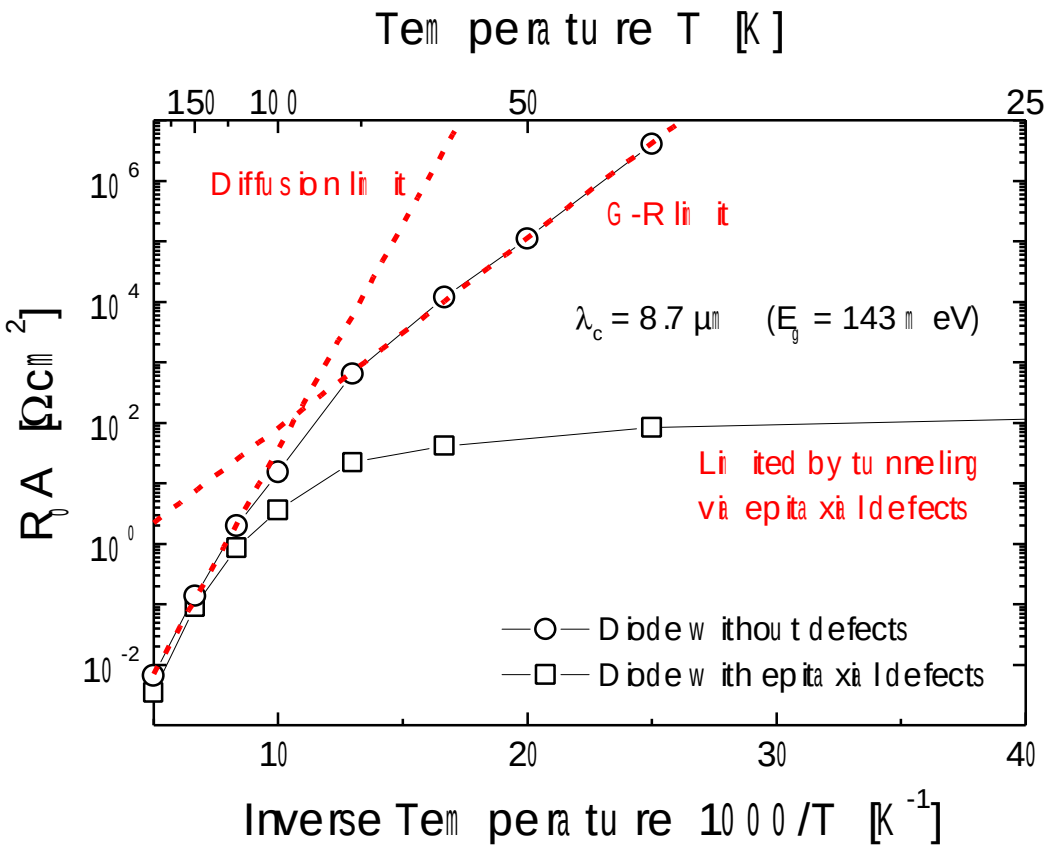
IV Analysis of 10 µm IRSLs



IAF
Fraunhofer Institut
Angewandte
Festkörperphysik

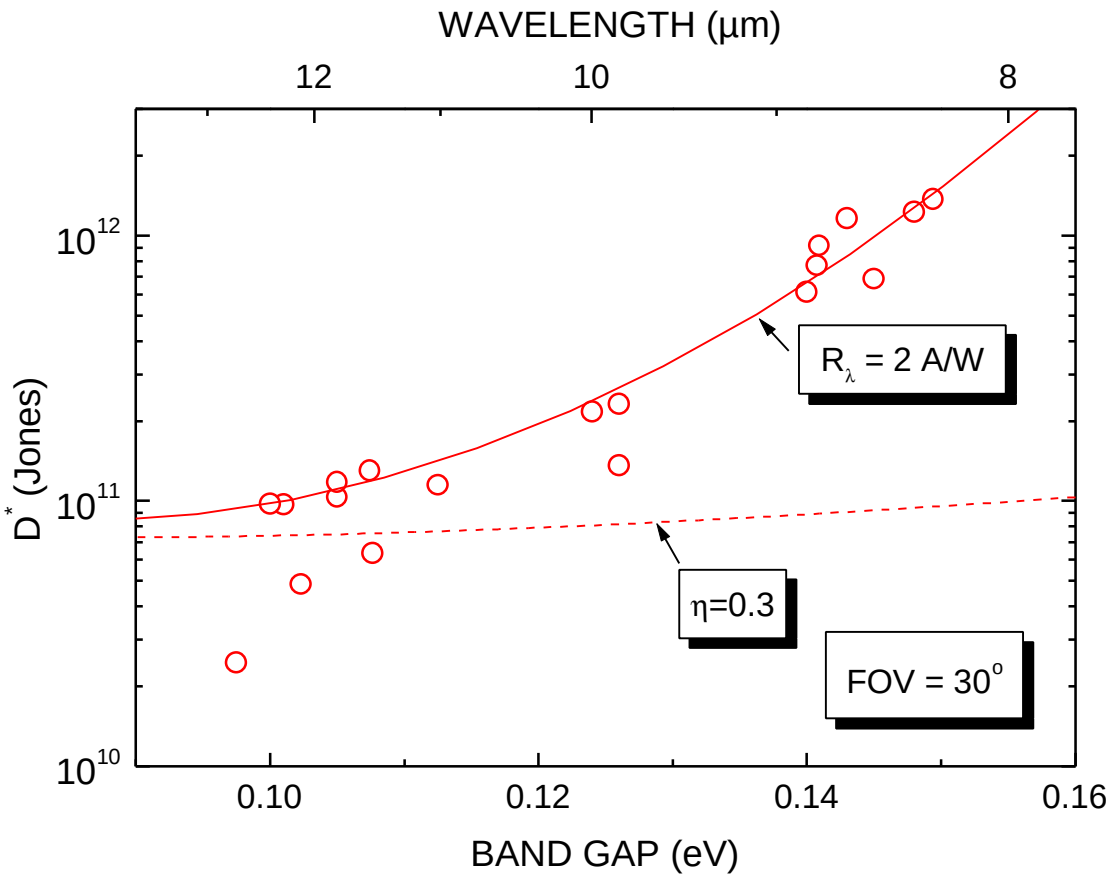
Temperature dependence of R_0A

- Limited by G-R currents at lower temperatures
- Minority carrier lifetime: 13 ns
  G-R lifetime: 28 ns
  (results dependend on model)
- Suppression of trap-assisted tunneling due to
  - low trap density
  - large out-of-plane reduced effective mass



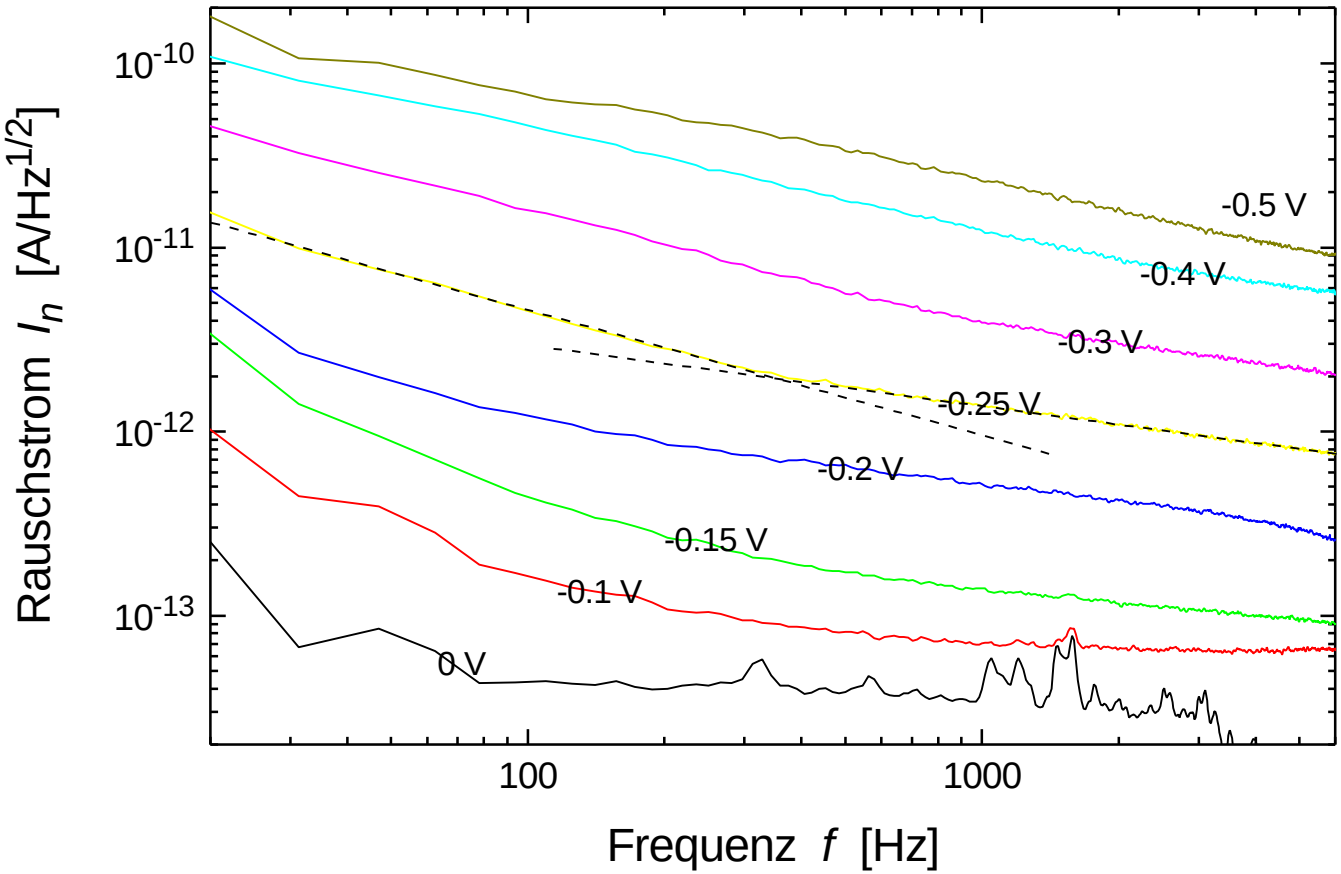
Fraunhofer Institut Angewandte Festkörperphysik

Single-element diodes: BLIP at 77 K



IAF
Fraunhofer Institut
Angewandte
Festkörperphysik

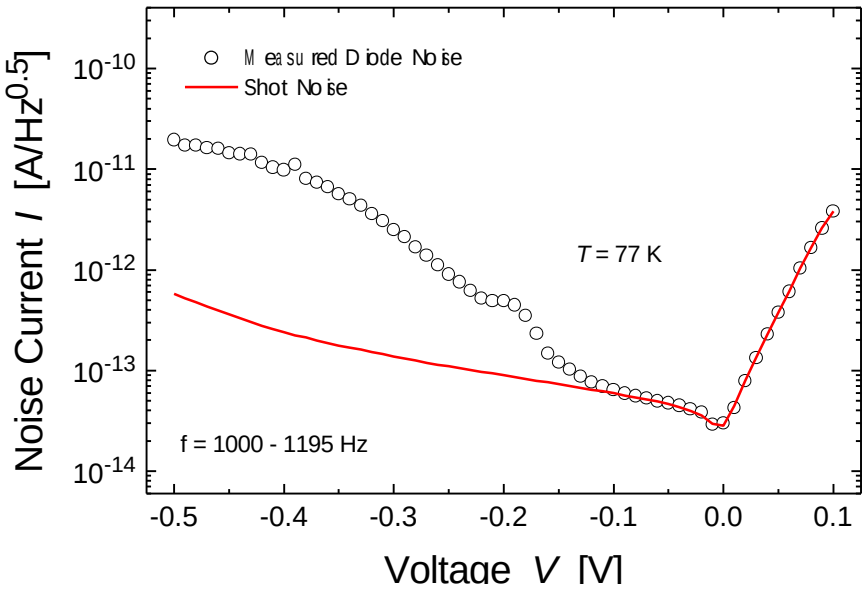
Noise Measurements



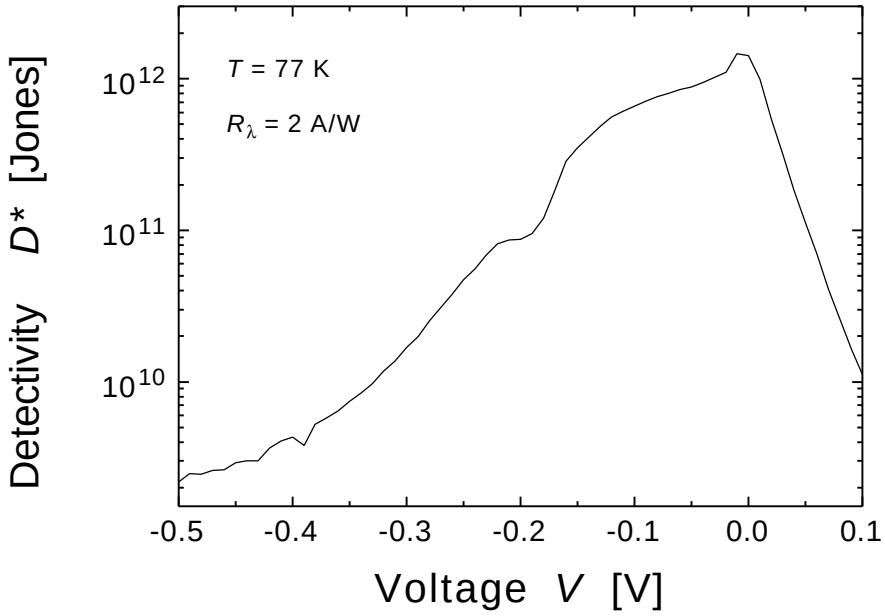
IAF
Fraunhofer Institut
Angewandte
Festkörperphysik

Noise Measurements

⇒ Noise Current



⇒ Detectivity



Fraunhofer Institut
Angewandte
Festkörperphysik

Surface leakage currents: Passivation (8 µm cut-off)

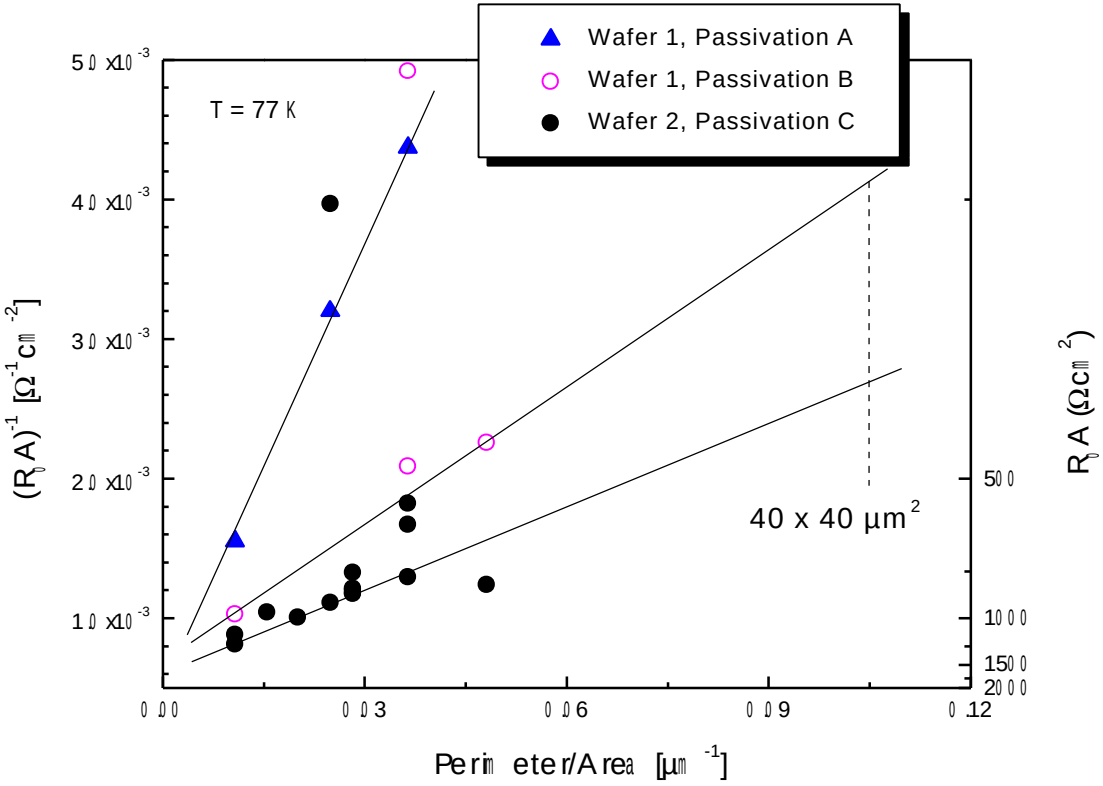
$$\left(R_0 A\right)^{-1} = \left(R_0 A\right)^{-1}_{bulk} + \left(R_0 A\right)^{-1}_{SL}$$

Surface leakage currents:

$$I_{SL} \propto P \quad \Leftrightarrow \quad \left(R_0\right)_{SL} \propto \frac{1}{P}$$

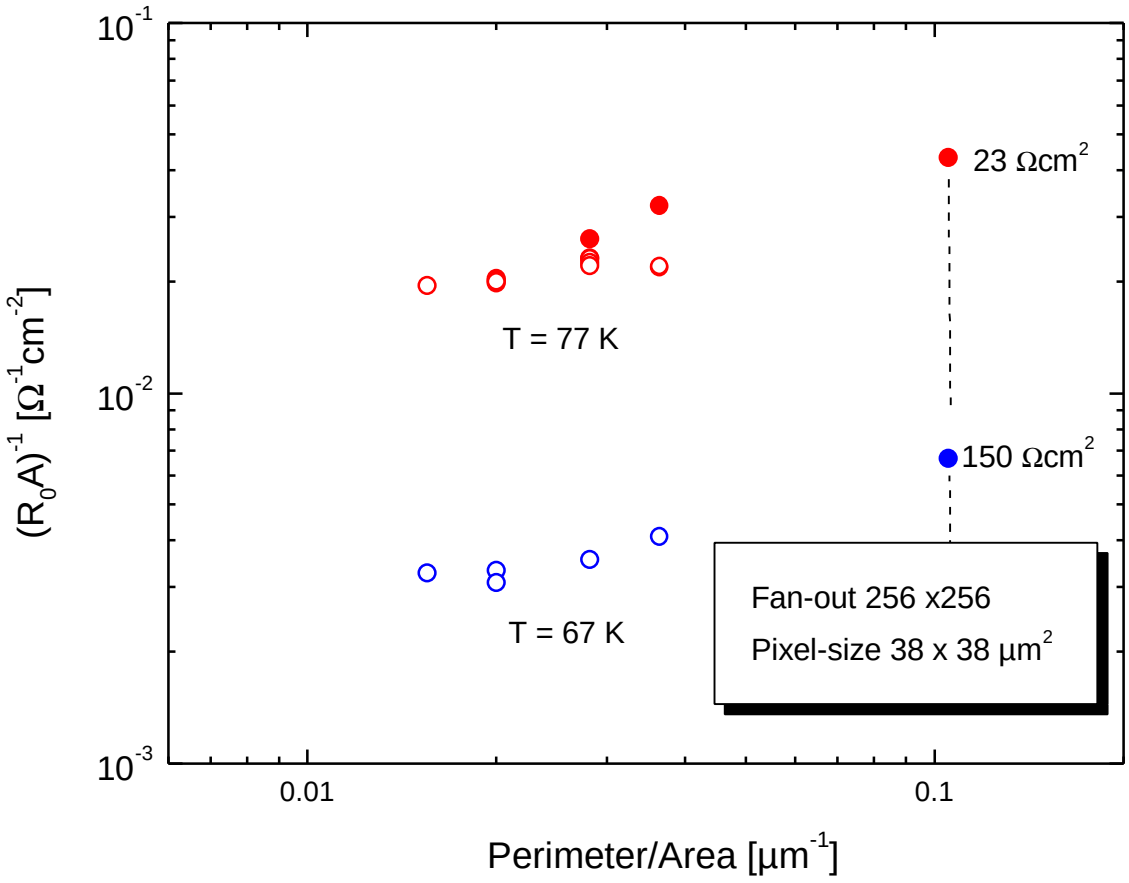
$$\Leftrightarrow \quad \left(R_0 A\right)_{SL} \propto \frac{A}{P}$$

$$\boxed{\left(R_0 A\right)^{-1}_{SL} \propto \frac{P}{A}}$$



Fraunhofer Institut Angewandte Festkörperphysik

Inverse R_0A versus Perimeter/Area, 10 µm cut-off

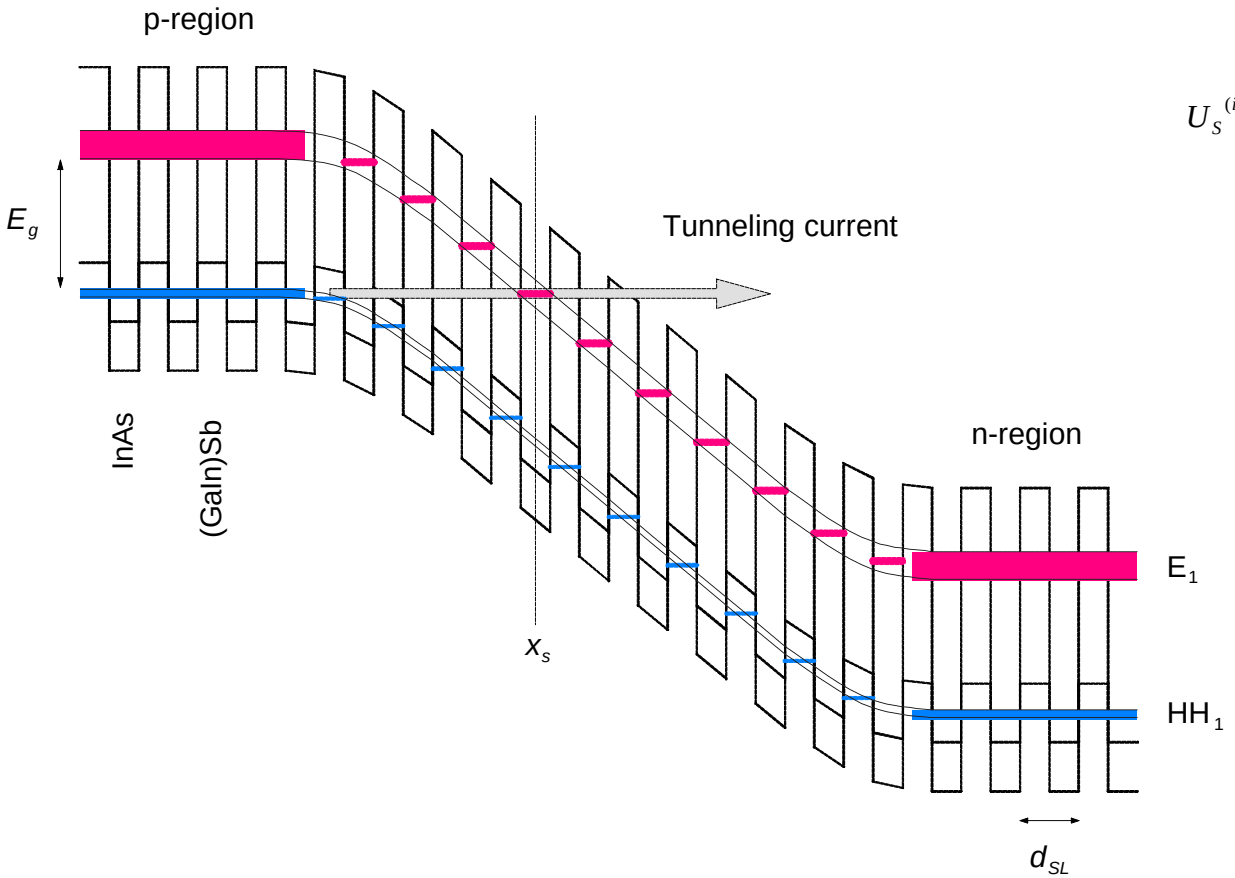


Fraunhofer Institut Angewandte Festkörperphysik

Wannier-Stark localization

Fraunhofer Institut
Angewandte
Festkörperphysik

Wannier-Stark localization and Zener tunneling

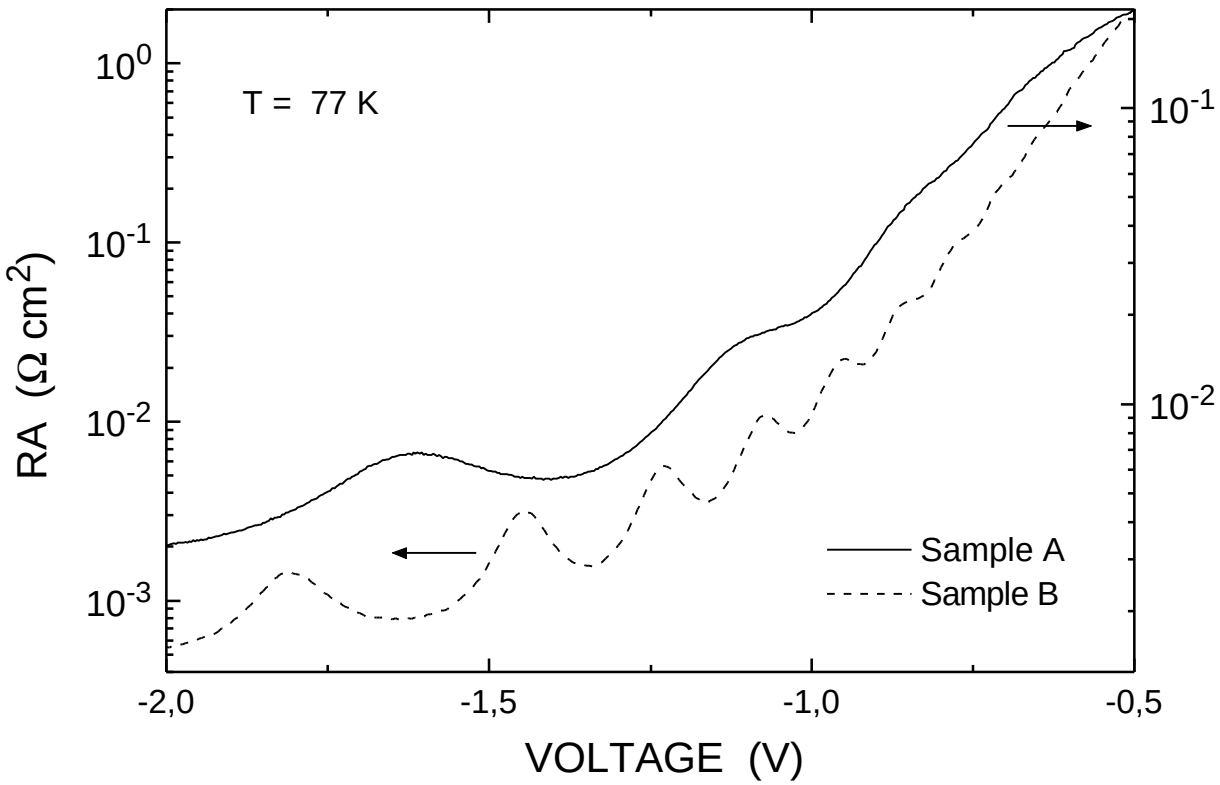


$$U_S^{(i)} = U_S^{(i-1)} - U_{bi}\left(\frac{d_{SL}^{\,2}}{d_p^{\,2}} + \frac{2d_{SL}}{d_p}\sqrt{1-\frac{U_S^{(i-1)}}{U_{bi}}}\right)$$

$$d_p = \sqrt{\frac{2eU_{bi}}{e}\,\frac{N_D/N_A}{N_A+N_D}}$$

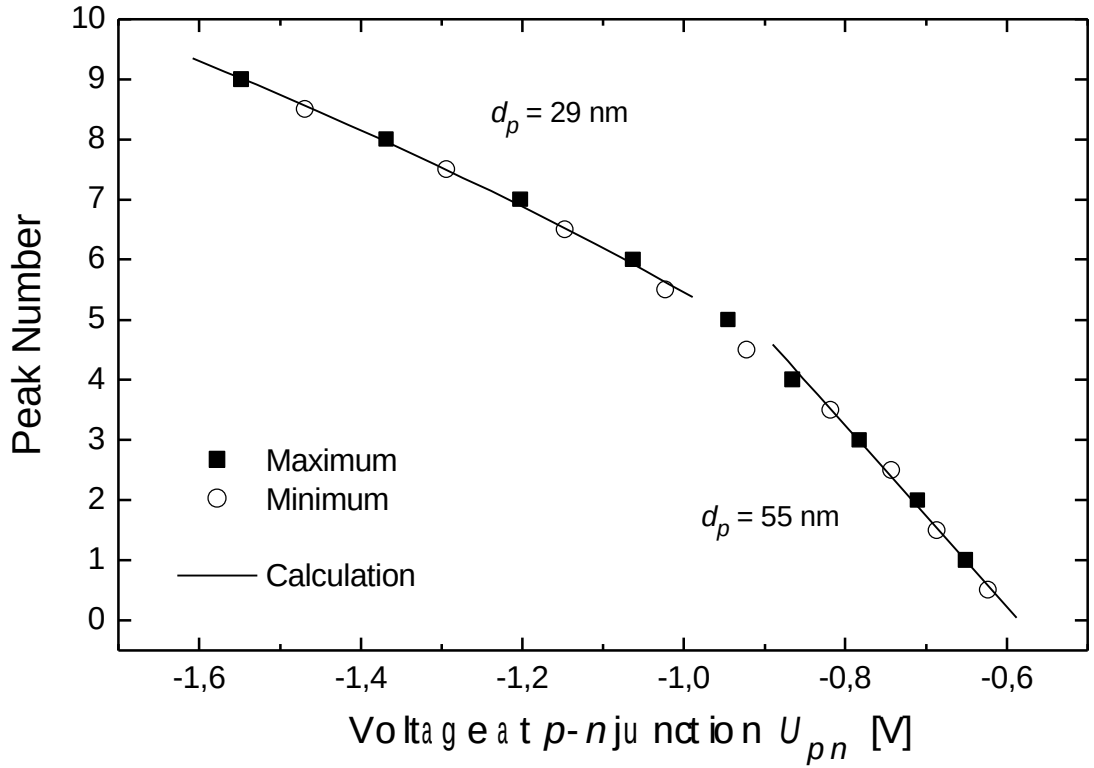
Fraunhofer Institut Angewandte Festkörperphysik

Oscillations observed in the dynamical impedance



L. Bürkle, F. Fuchs, E. Ahlswede,
W. Pletschen, J. Schmitz,
Physical Review B 64, 045315 (2001)

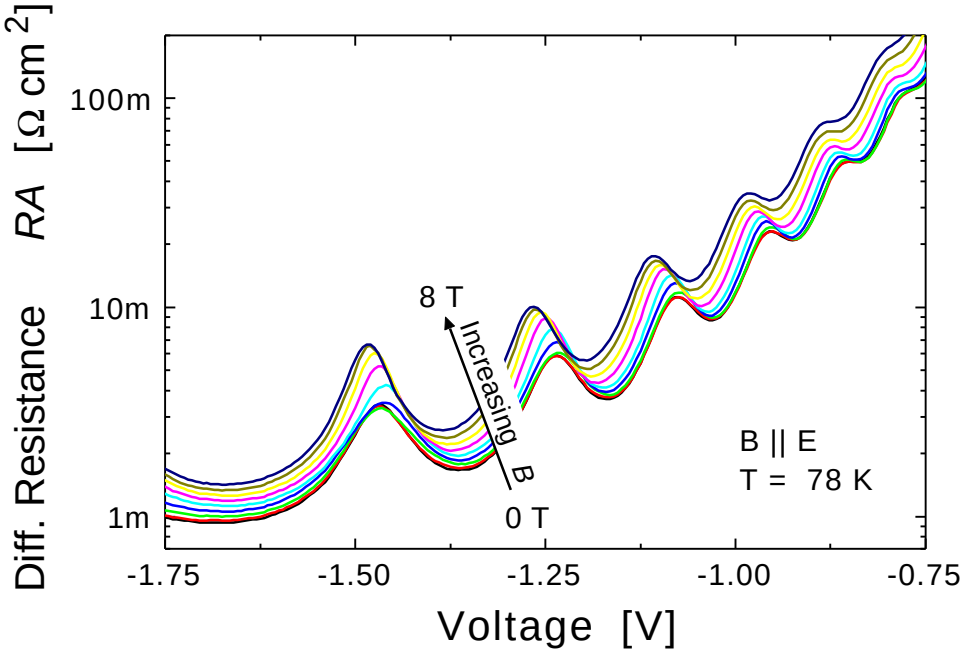
IAF
Fraunhofer Institut
Angewandte
Festkörperphysik



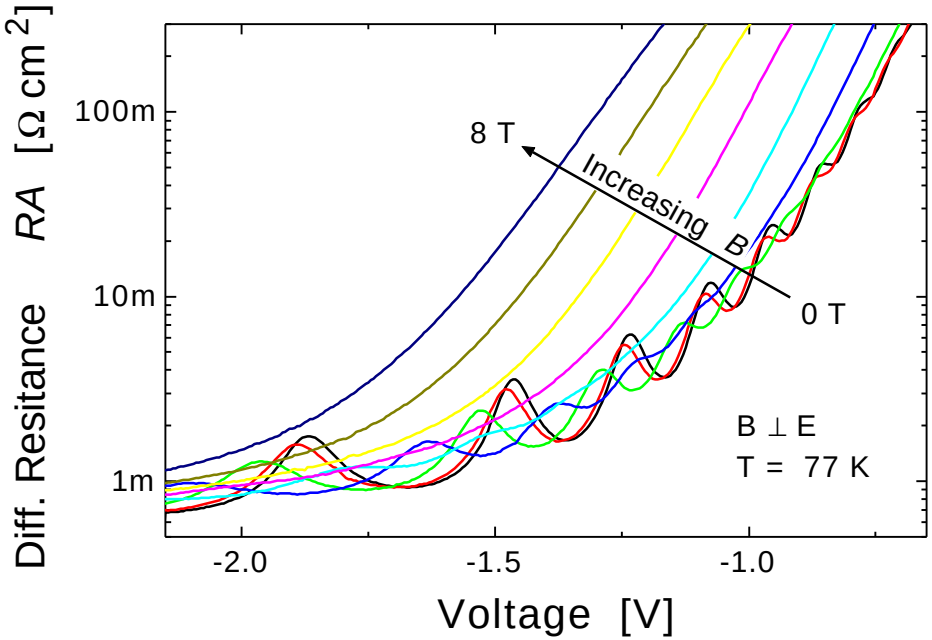
Fraunhofer Institut Angewandte Festkörperphysik

Wannier-Stark Oscillations in a Magnetic Field

⇒ Magnetic field || built-in Electric field

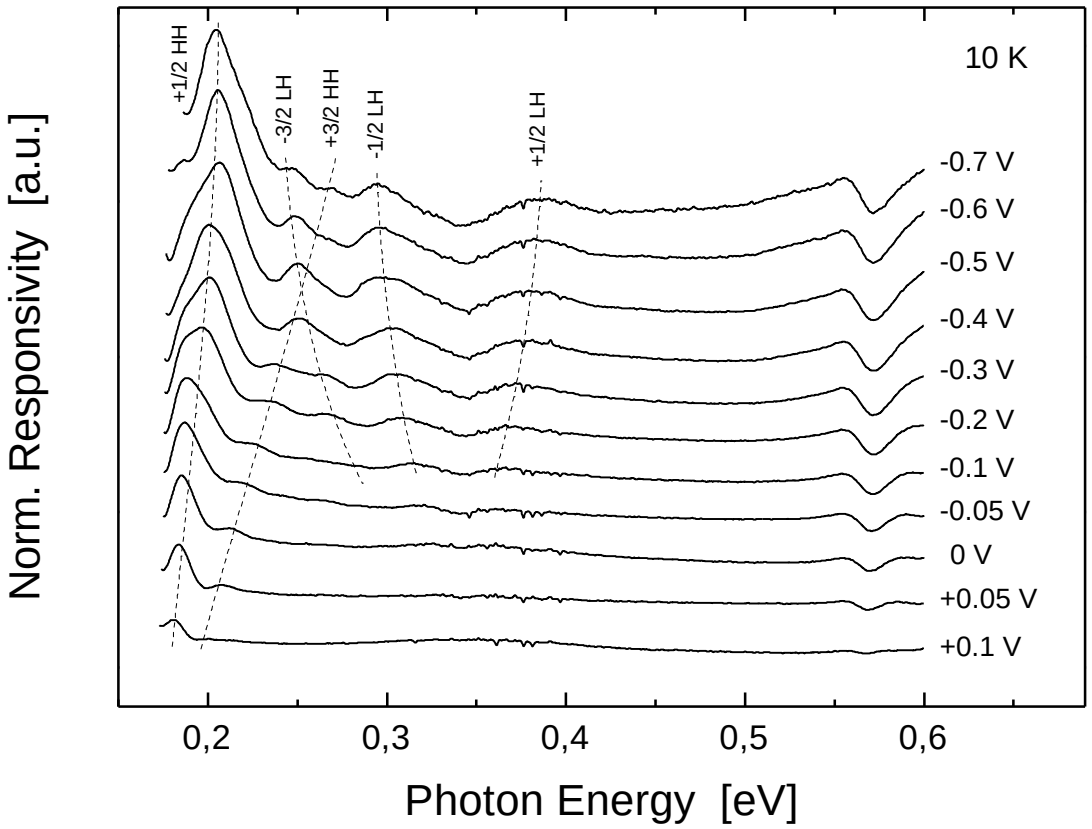


⇒ Magnetic field ⊥ built-in Electric field



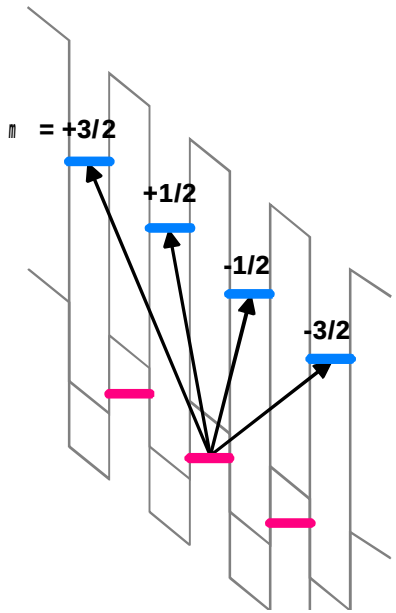
Fraunhofer Institut Angewandte Festkörperphysik

Wannier-Stark localization observed in the photoresponse

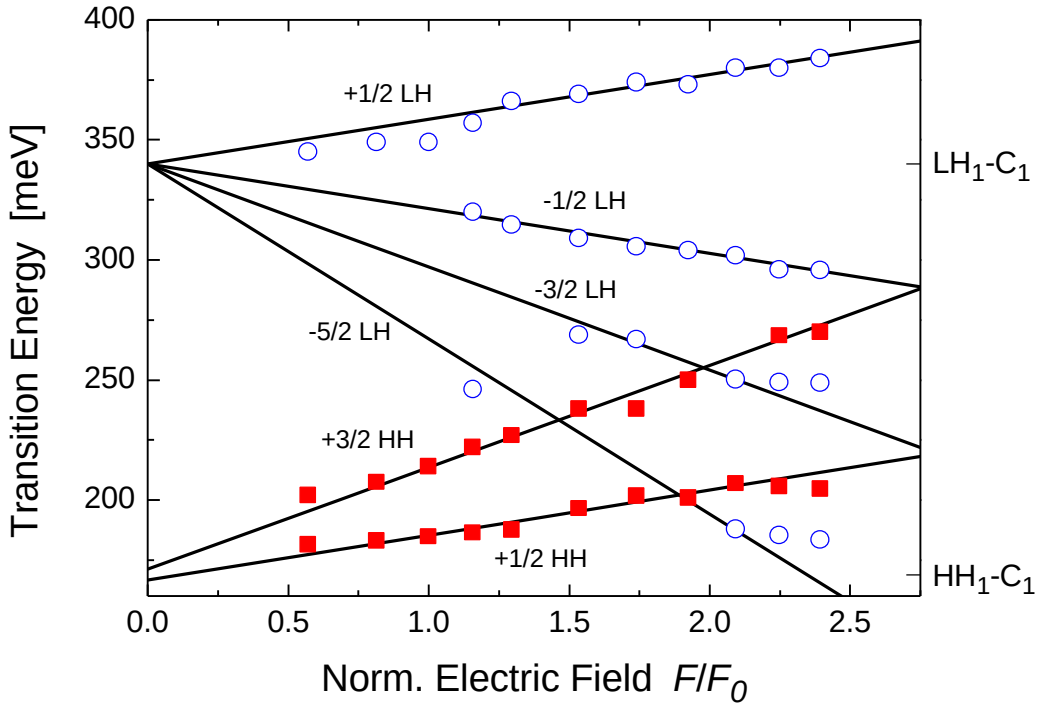


Fraunhofer Institut
Angewandte
Festkörperphysik

Optical transitions between Wannier-Stark states



$$E_m = E_0 + mqFd_{SL}$$



Fraunhofer Institut Angewandte Festkörperphysik

— Summary

- High Reproducibility of MBE growth
- Residual background in low gap SLs 5 - 8 x 10^{15} cm^{-3}
- Detector performance, cut-off 8 µm - 10 µm: $D^* > 10^{12}$ Jones - 2 x 10^{11} Jones)
- Stable passivation tested for 256 x 256 FPA hybrides
- Observation of Wannier-Stark localization

IAF
Fraunhofer Institut
Angewandte
Festkörperphysik

Co-workers

- MBE-Growth: J. Schmitz, M. Walther
- X-Ray: N. Herres, H. Güllich
- Raman: J. Wagner
- AFM: S. Müller, C. Hoffmann, P. Hiesinger
- Processing: W. Pletschen, R. Kiefer, E. Sah, J. Schleife
- Electro-Optical Characterization, Magneto-Transport: L. Bürkle, R. Hamid, K. Schwarz
- 4 x 4 EFA Calculations: L. Bürkle, Q. Yang
- Continuous support: G. Weimann, P. Koidl

Some references of presented data

L. Bürkle, F. Fuchs, J. Schmitz, W. Pletschen,
Control of the residual doping of InAs/(GaIn)Sb infrared superlattices
Applied Physic Letters, Vol. 77, 1659 (2000)

L. Bürkle, F. Fuchs, R. Kiefer, W. Pletschen, E. Sah, J. Schmitz
Electrical characterization of InAs/(GaIn)Sb infrared superlattice photodiodes for the 8 to 12µm range
Mat. Res. Soc. Symp. Proc. Vol. 607, p.77 (2000)

F. Fuchs, L. Bürkle, R. Hamid, W. Pletschen, J. Schmitz,
Optoelectronic properties of photodiodes for the mid- and farinfrared based on the InAs/GaAs/AlSb materials family
Proc. SPIE, 4288, p.171 (2001)

L. Bürkle, F. Fuchs, E. Ahlswede, W. Pletschen, J. Schmitz,
Wannier-Stark localization in InAs/(GaIn)Sb superlattice diodes
Physical Review B 64, 045315 (2001)