HOT longwave InAs/InAsSb superlattice cascade photodiodes

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Outline

- III-V antimonide detectors technology at VIGO
- InAs/InAsSb SLs – natural substitute for MCT
- Cascade detectors – background and motivation
- LWIR InAs/InAsSb SL cascade detectors
- Comparison with VIGO bulk MCT detectors
- Conclusions and outlook

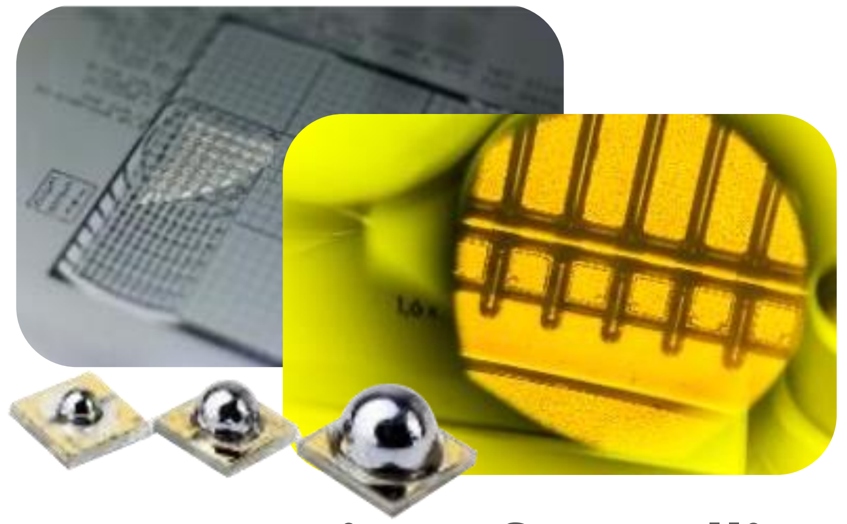
III-V antimonide detectors technology at VIGO

VIGO PHOTONICS

1.EPITAXY

Growth of detector heterostructures by MBE.

2. PROCESSING



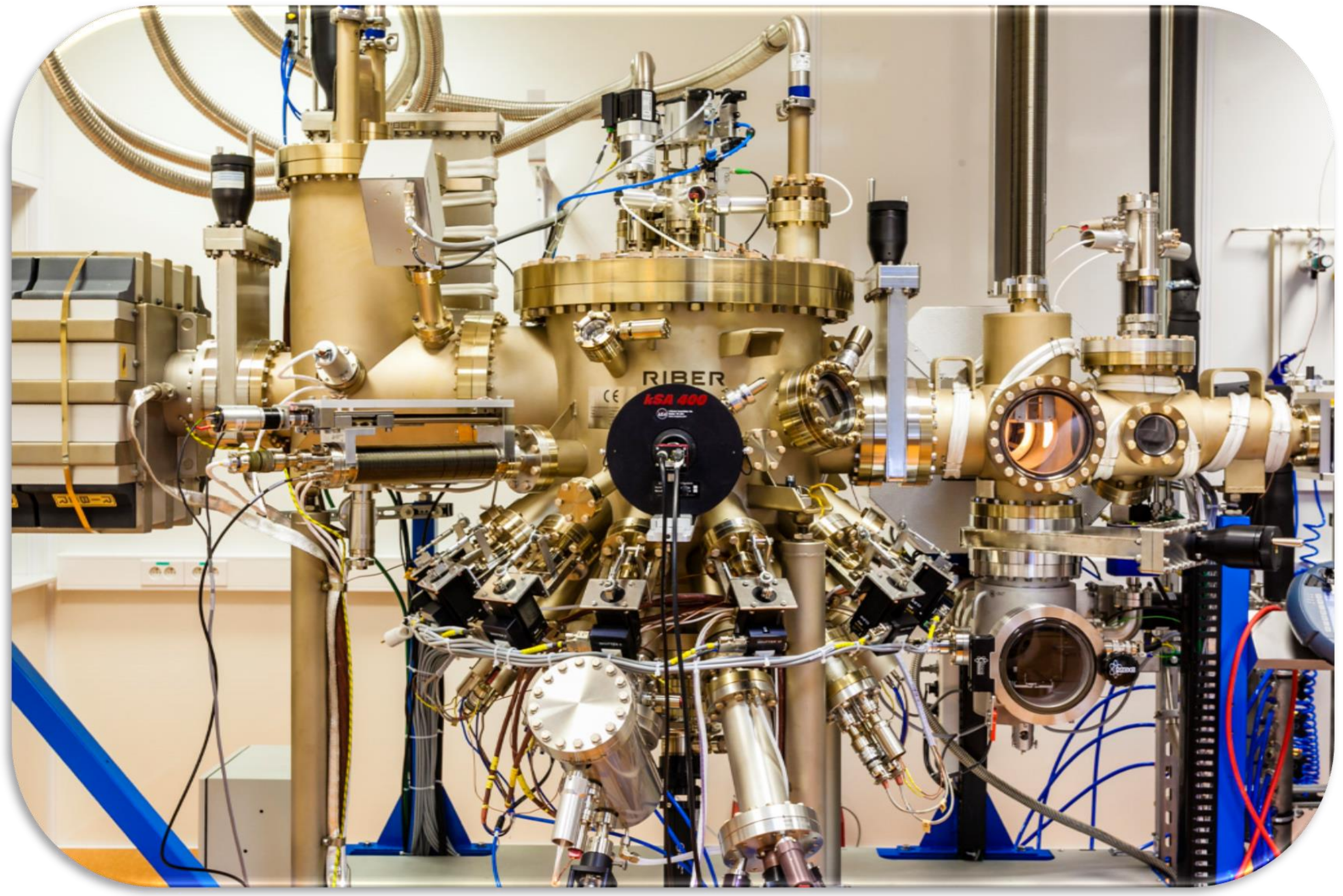
Evaporation of metallic and dielectric layers, etching, photolithography, dicing and micromachining of immersion lenses.

3. PACKAGING

Automated assembly, packaging and characterization of IR detectors.

4. INTEGRATION WITH ELECTRONICS

Dedicated electronics integrated with IR detectors – detection modules.



Riber Compact 21 DZ MBE system

- VIGO-MUT joint laboratory
- 12 sources
- 1x3” wafer per run
- InAs/InAsSb superlattices and bulk materials
- MWIR and LWIR detectors

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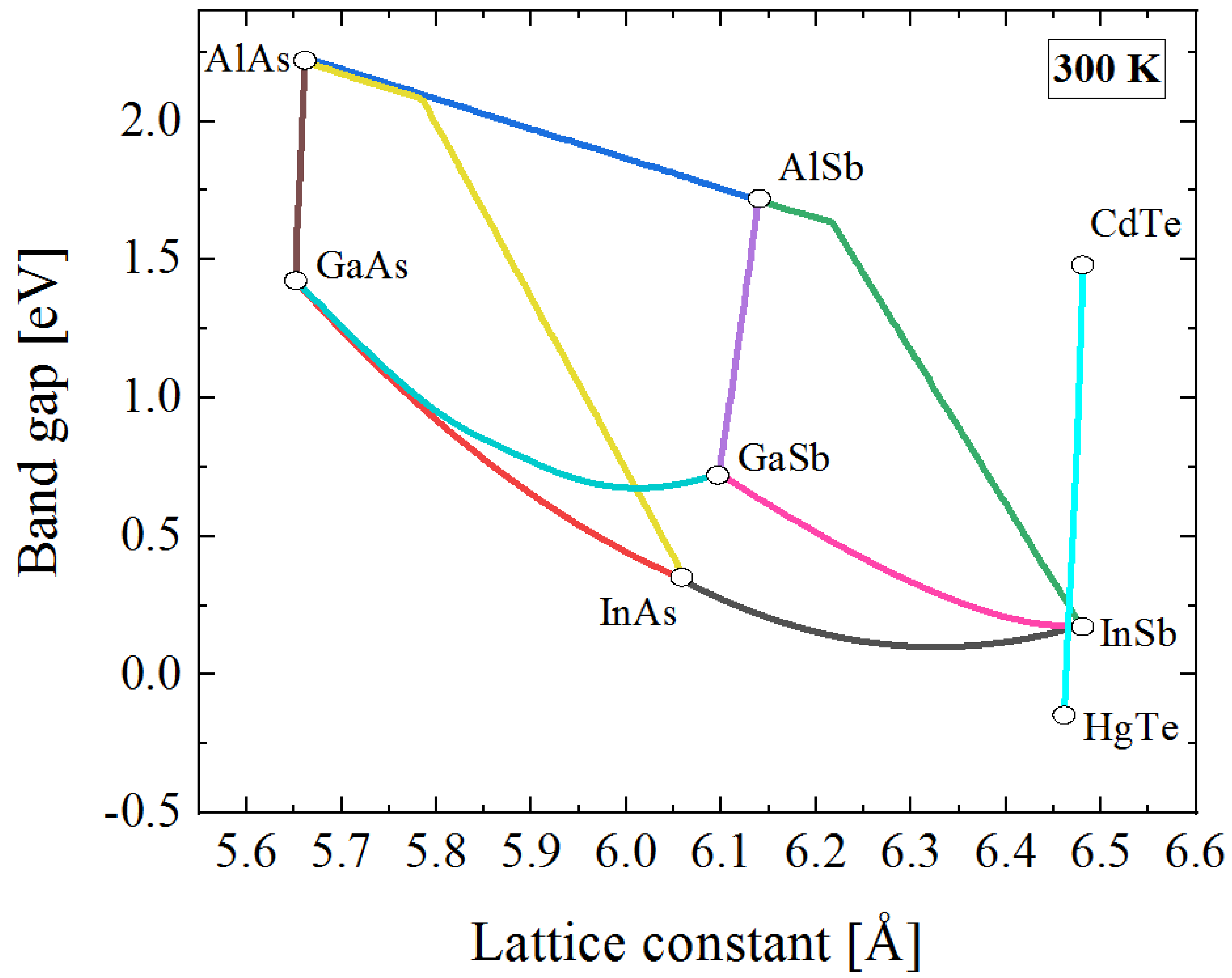
InAs/InAsSb SLs – natural substitute for MCT

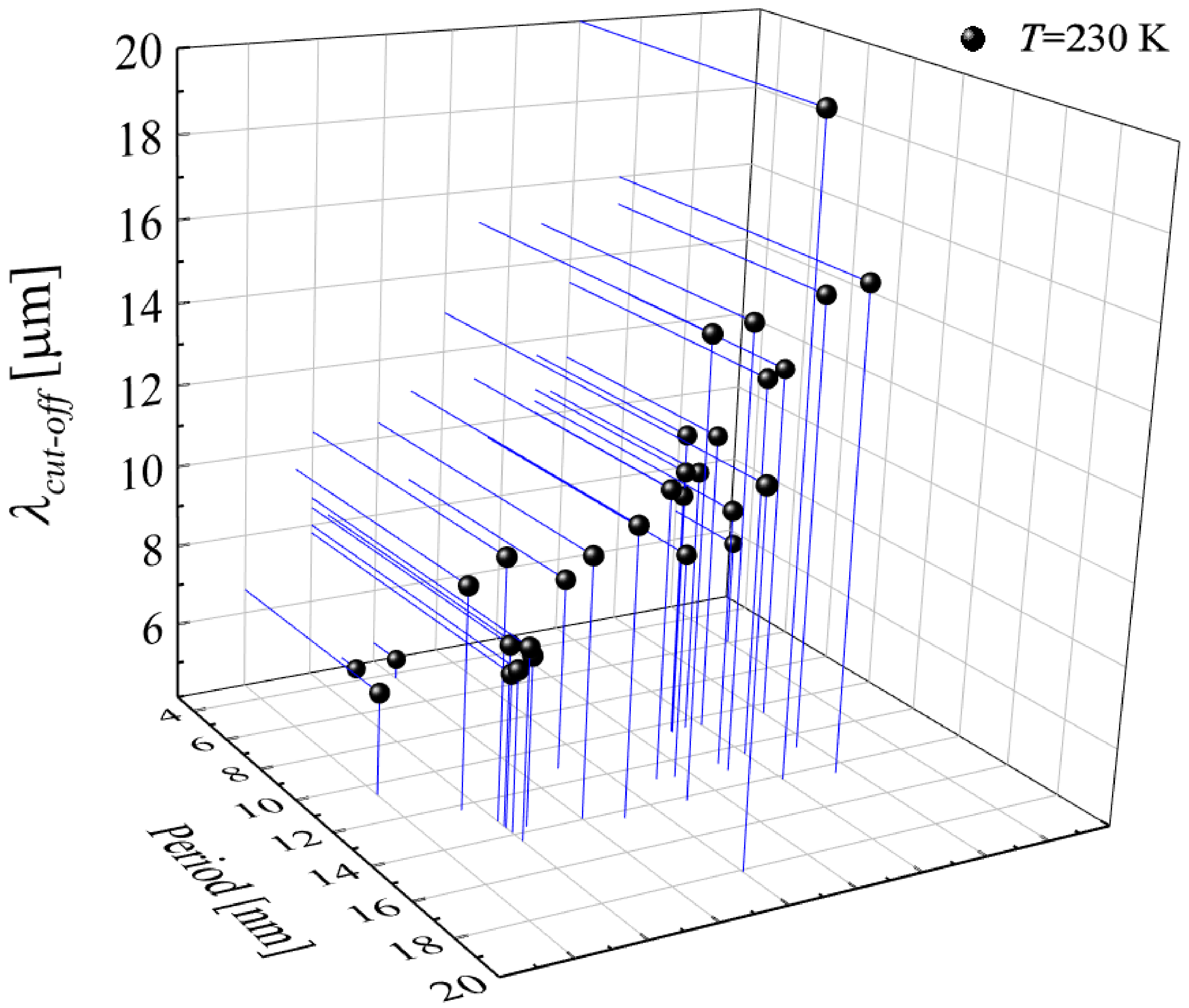
MCT

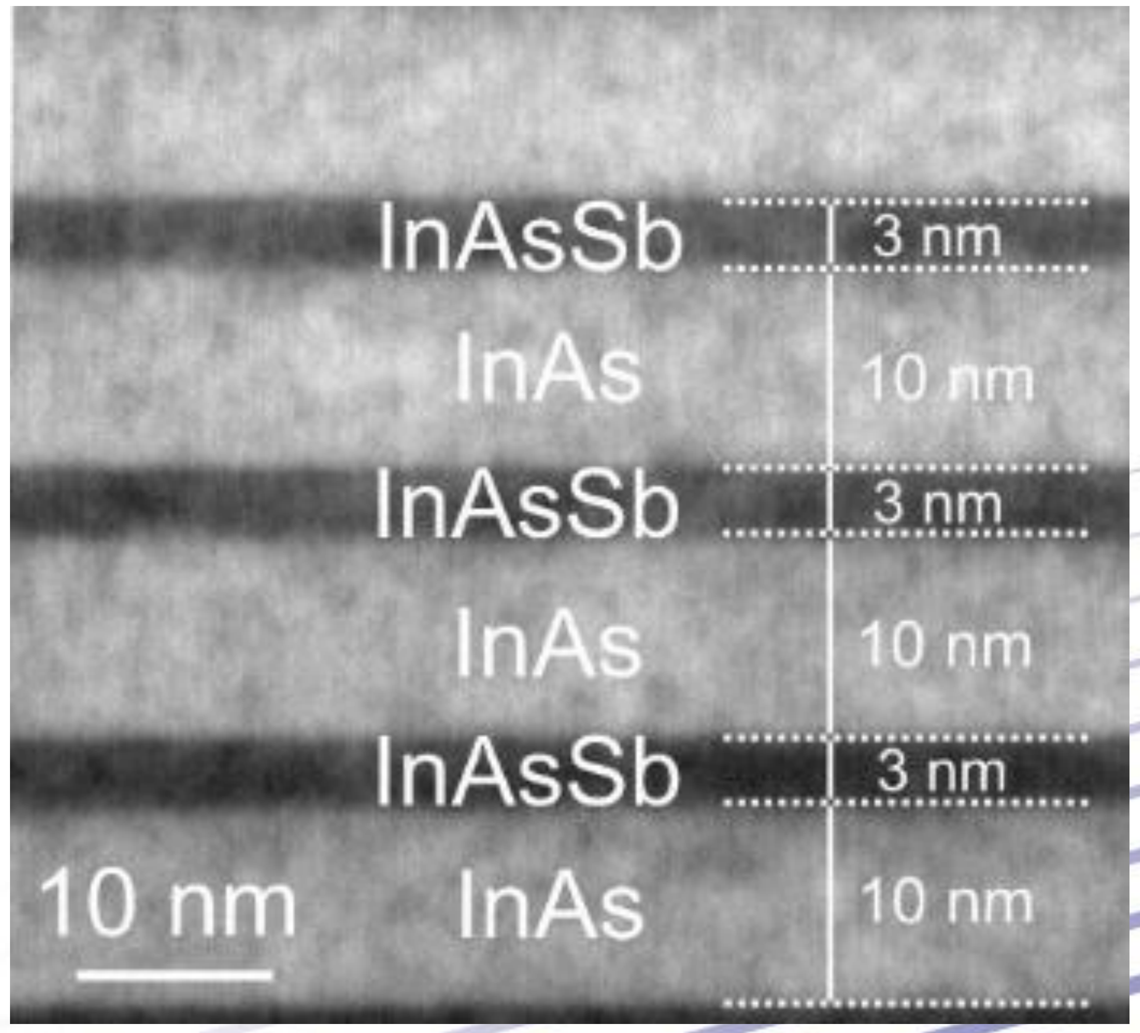
- CdTe on GaAs – universal buffer for MCT
- Control of Eg by varying Hg to Cd ratio
- Near perfect lattice-match to Cd(Zn)Te
- Poor thermal, chemical and mechanical stability
- Fundamentally, the best material for IR detection due to the highest *α/G*

InAs/InAsSb SLs

- GaSb grown with IMF mode on GaAs – universal hybride substrate for SLs
- Eg controlled by varying SL period/composition
- Covers spectral range from MWIR up to VLWIR
- Average SL lattice constant matched to the buffer
- Strain control during MBE growth
- Better thermal and mechanical stability



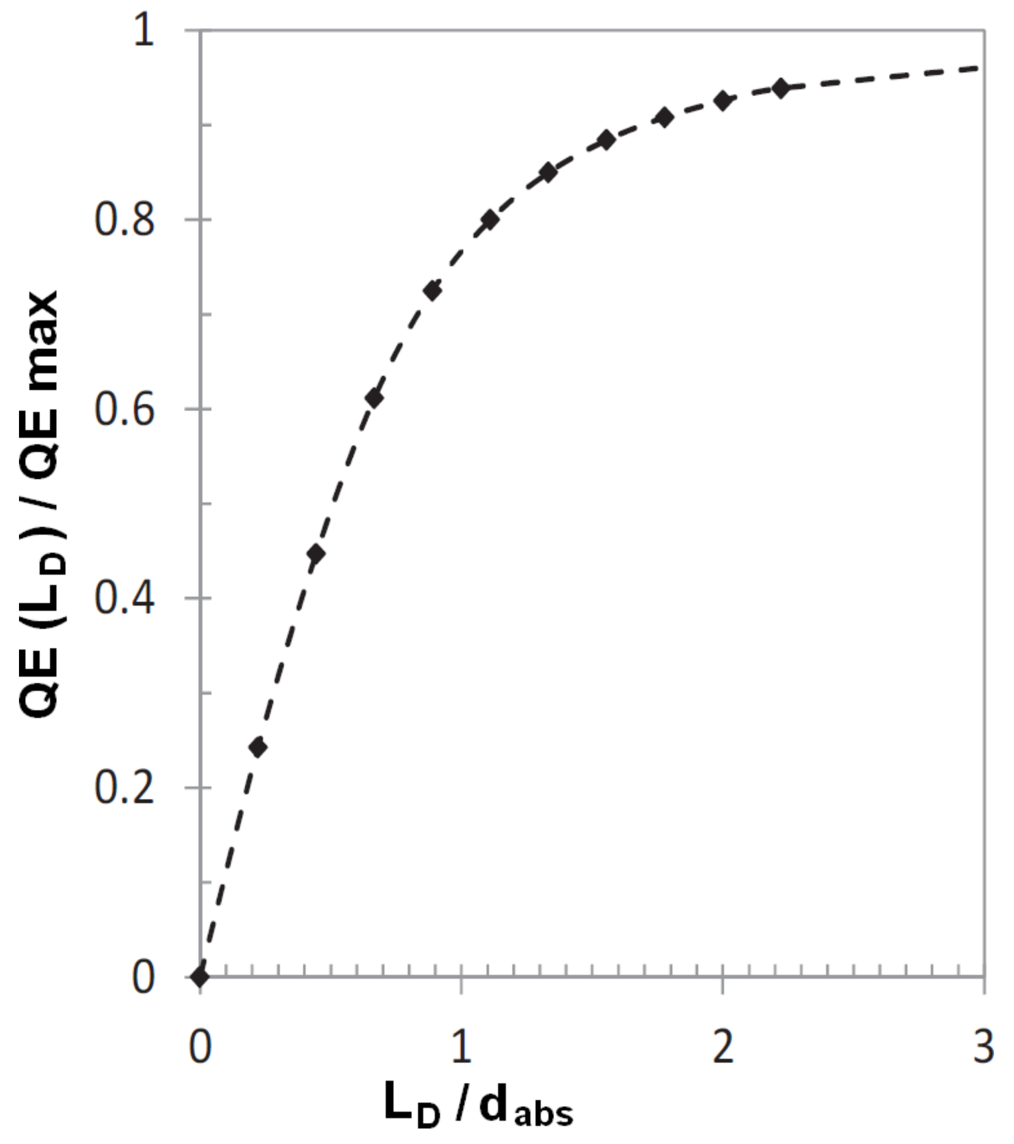




Cascade detectors – motivation for development

Factors limiting quantum efficiency of conventional LWIR devices operating at near room temperatures:

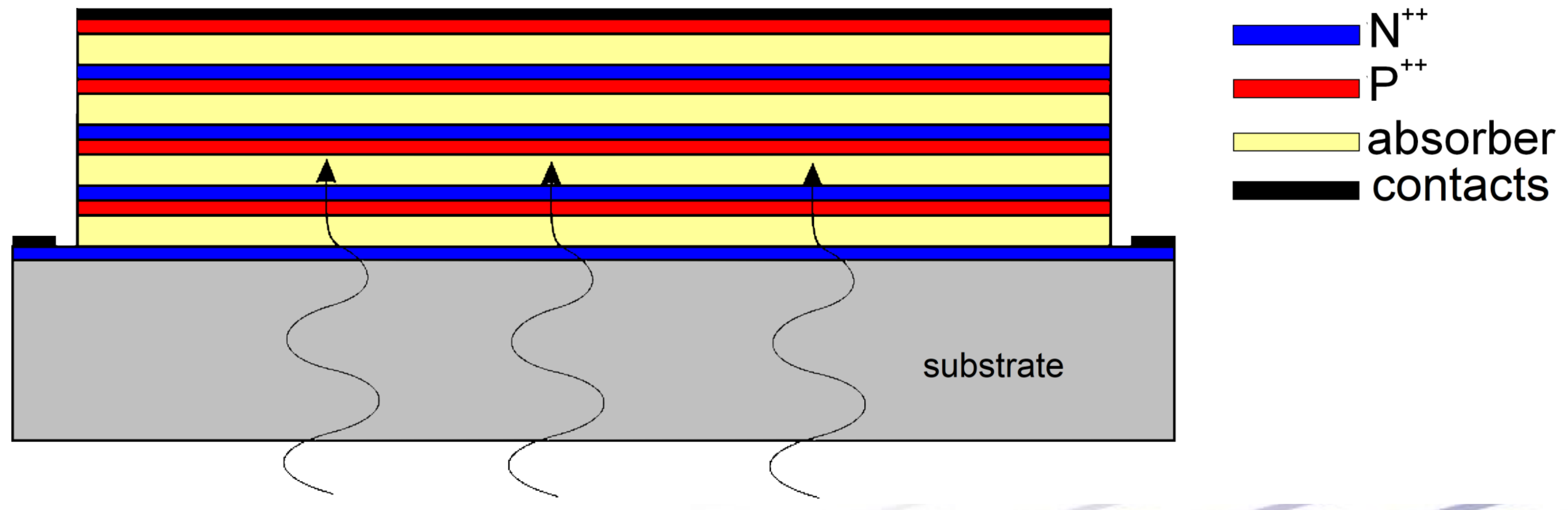
- **Absorption depth (1/α) larger than vertical diffusion length L_D**, which can be lower than 1 µm;
- **Extremely low junction resistance R_d** close to or lower than parasitic **series resistance R_s**.



Adopted from: Klipstein *et al.*, doi: 10.1016/j.infrared.2018.11.022

Cascade design **overcomes these issues** by:

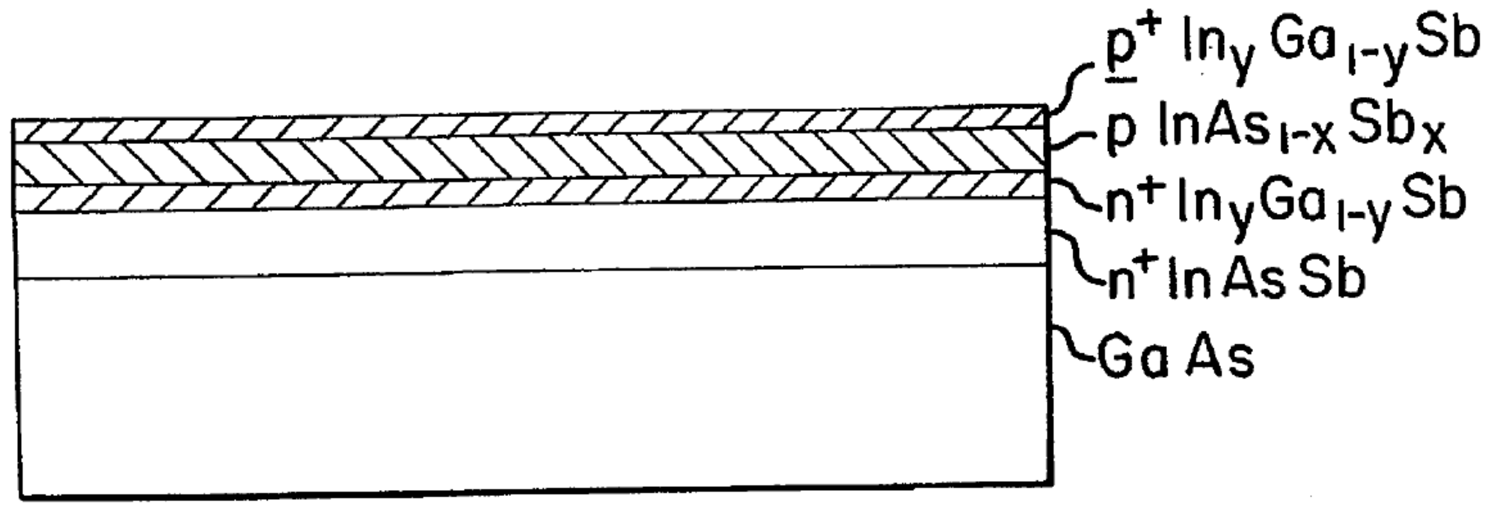
- Using **thin photovoltaic cells**, with $d_{abs}<L_D$ => **efficient and fast collection** of charge carriers;
- Connecting the **PV cells in series** with low-resistance junctions => increased resistance of the device ∝ n^2, easier coupling with the electronics.



Cascade detectors – historical perspective

VIGO PHOTONICS

- VIGO and Military University of Technology works on ICIPs from early 1990s [1]:
  - Horizontal or veritcal ICIP consisting of modified PiN structures connected by heavily doped tunnel junctions
  - Vertical design difficult to achieve for MCT grown by MOCVD due to technological and material issues: soft interfaces (interdiffusion) and limited arsenic doping efficiency

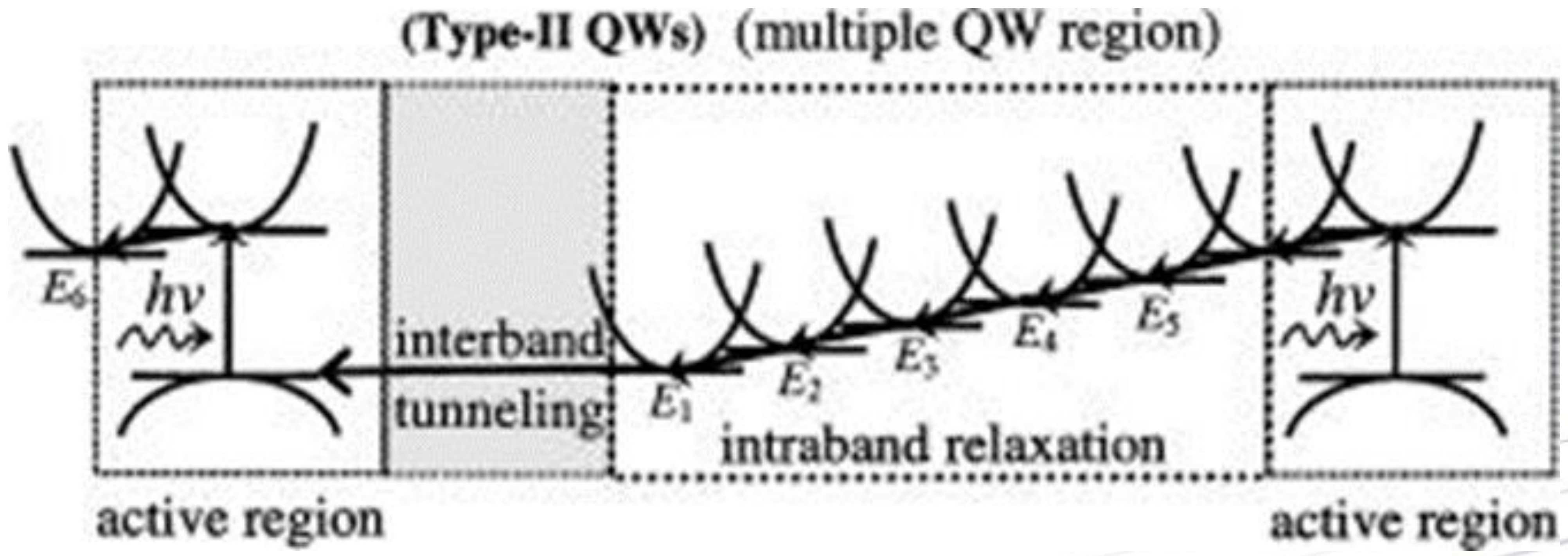


Example of single PV cell [2]

[1] J. Piotrowski, W. Gawron (1997). *Ultimate performance of infrared photodetectors and figure of merit of detector material. Infrared Physics & Technology, 38(2), 63–68*

[2] M. Razeghi, J. Piotrowski. *Multiple stacked Sb-based heterostructures*. U.S. Patent No. 5,650,635. 22 Jul. 1997.

- The concept was patented for bulk heterostructural InAsSb photodiodes on GaAs substrates [2]
  - The patent expired in 2015
- Interband cascade IR photodetectors based on T2SLs, stages connected with intraband relaxation layers – R. Yang [3].



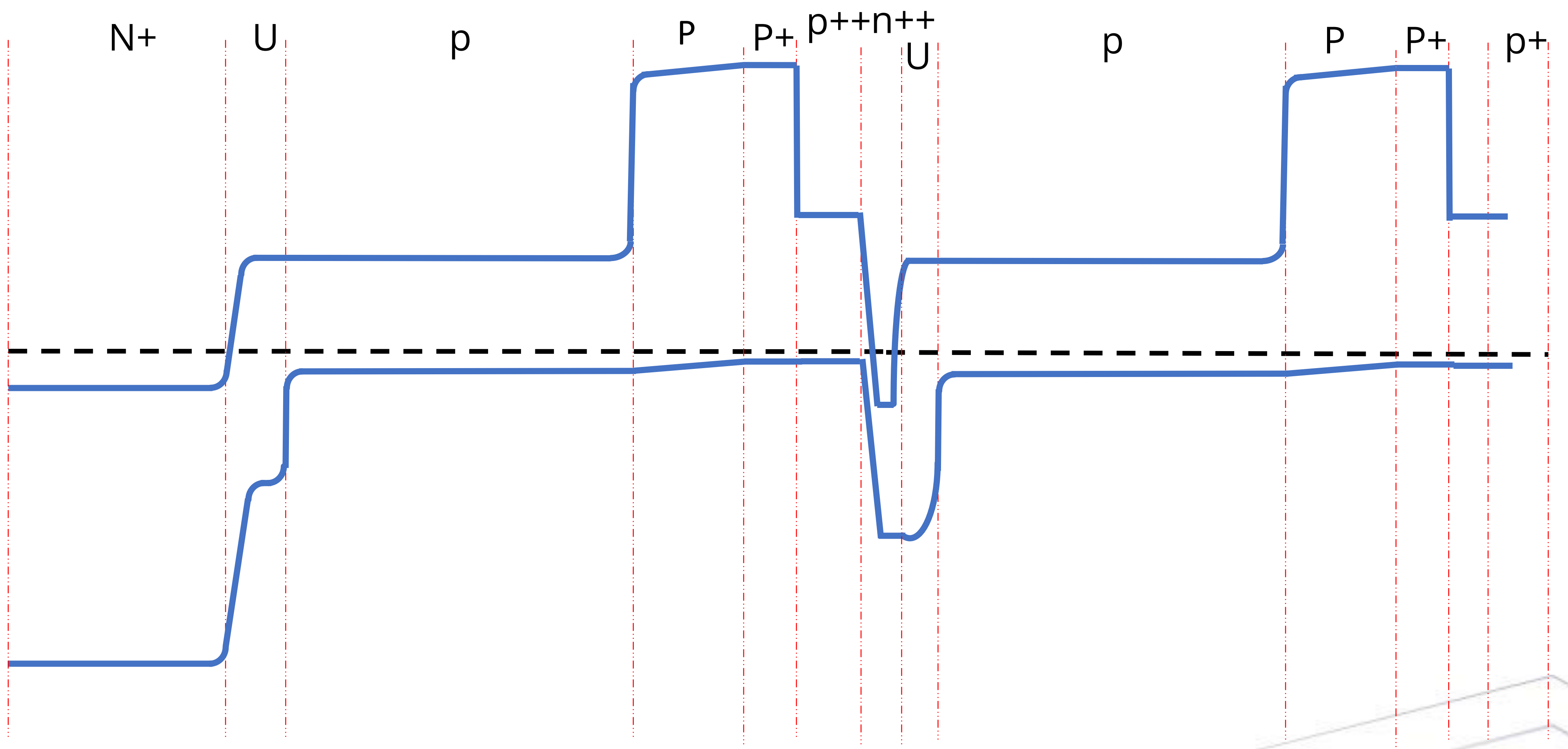
Connection of stages proposed by Yang [3]

[3] Li, J. V., Yang, R. Q., Hill, C. J., & Chuang, S. L. (2005). *Interband cascade detectors with room temperature photovoltaic operation*. Applied Physics Letters, 86(10), 101102.

Cascade detectors – background and motivation

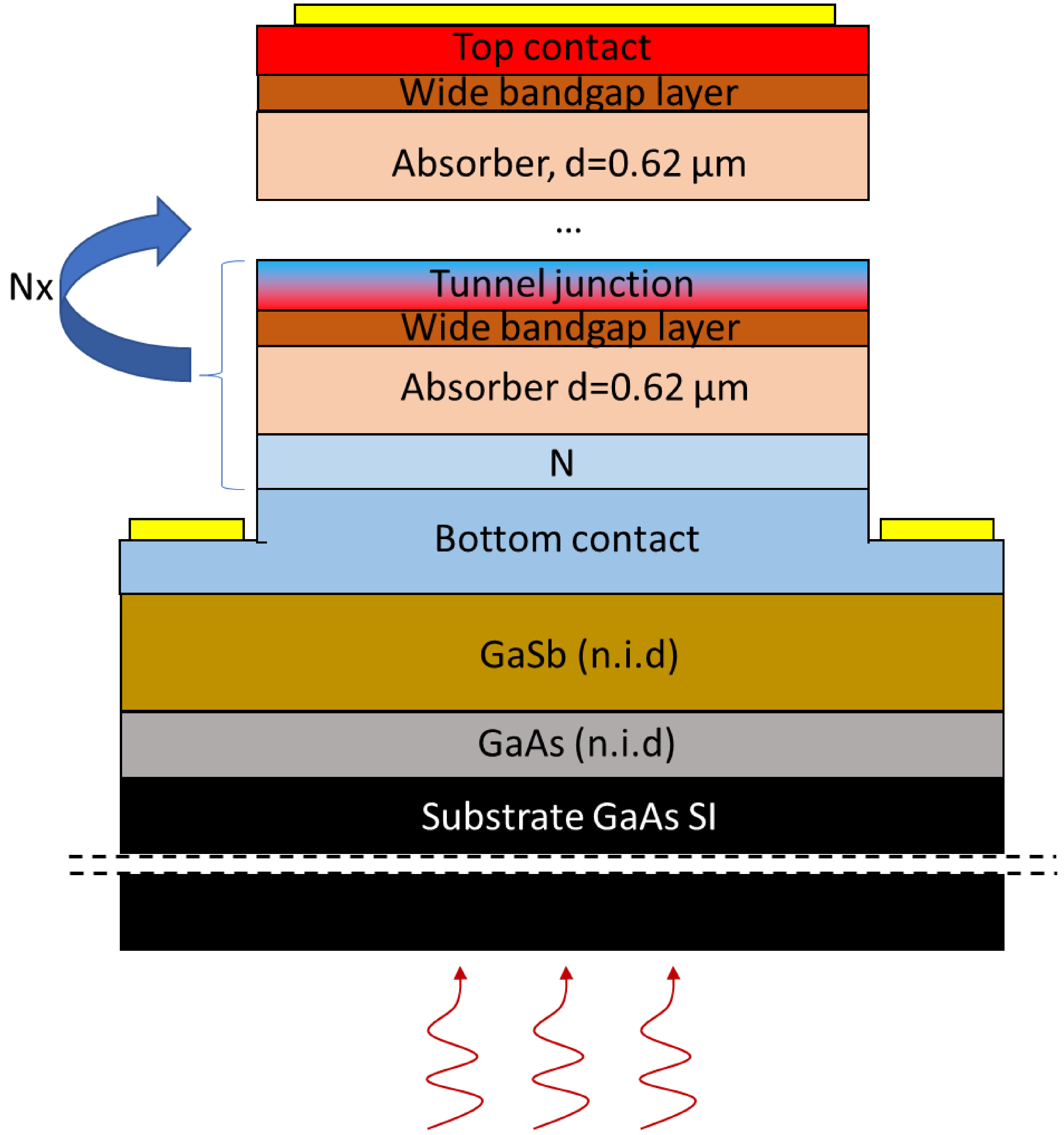
- **Objective**: substitute for HOT LWIR MCT PVM and PVMI detector; to continue the development of HOT detectors – VIGO domain
- III-V SLs grown by MBE are free of MCT technological limitations:
  - High doping is possible - **N_a and N_d (>1E19 cm^{-3})** - important for low resistance PV cells connections
  - **Sharp interfaces**, sublayer in SLs thickness <2 nm
- **Idea**: implementation of cascade concept with III-V SLs grown on low-cost IR-transparent GaAs substrate, important for the backside illuminated devices and devices with monolithically integrated microoptics, e.g. immersion lenses.

- **Applications: FTIR, laser spectroscopy**
- **Expected lower 1/f noise compared to widely used PC detectors**



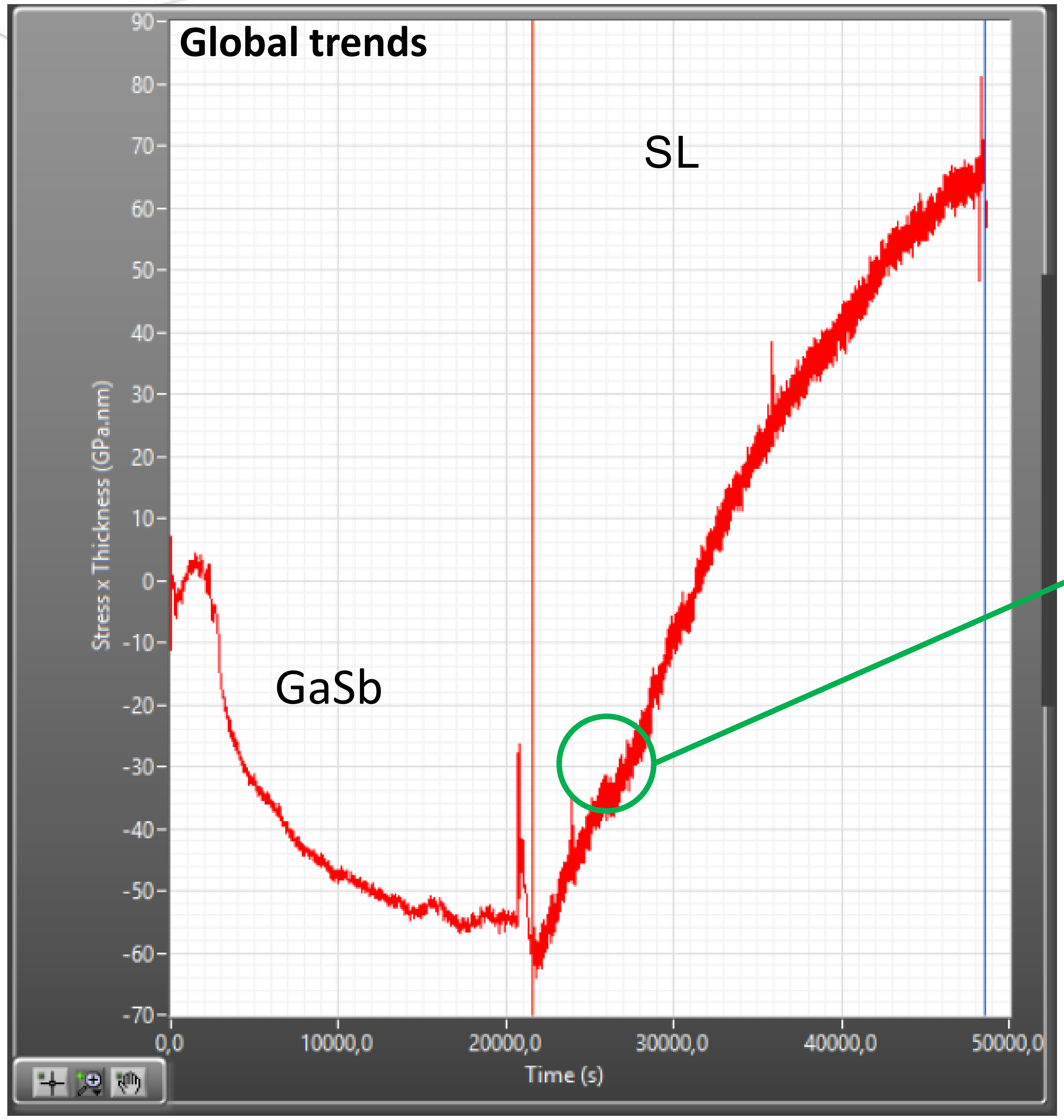
Schematic energetic structure

LWIR InAs/InAsSb SL cascade detectors – design

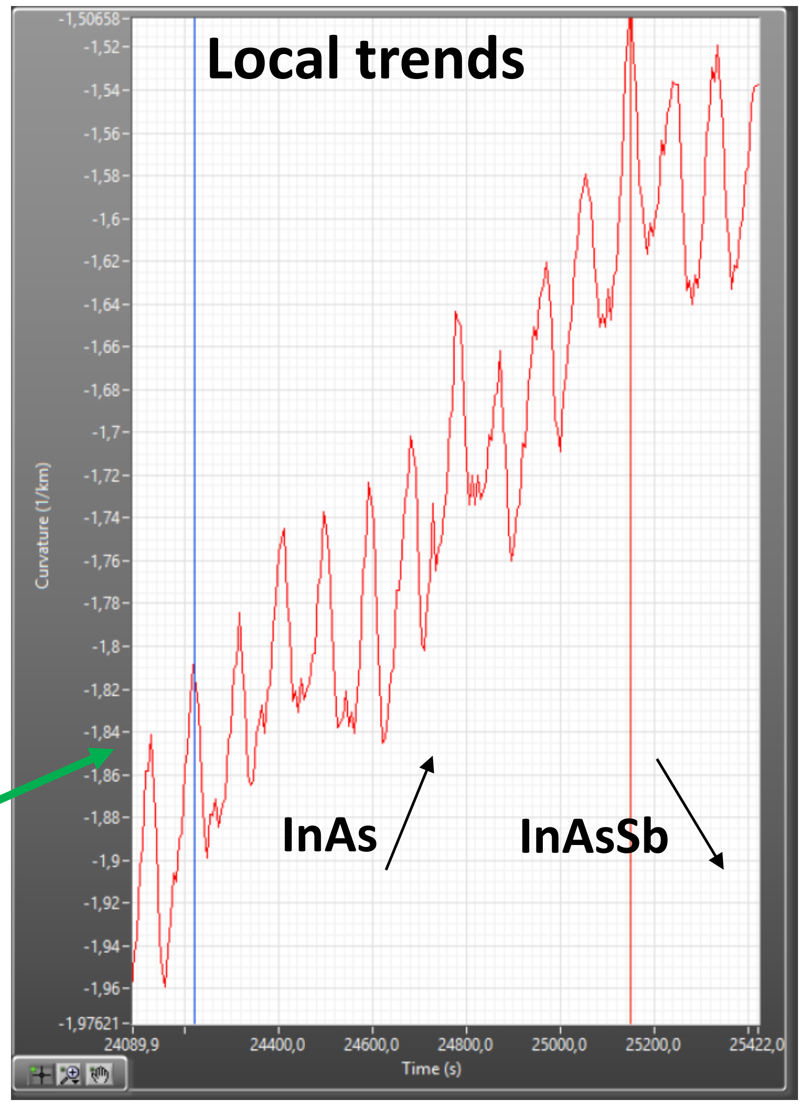


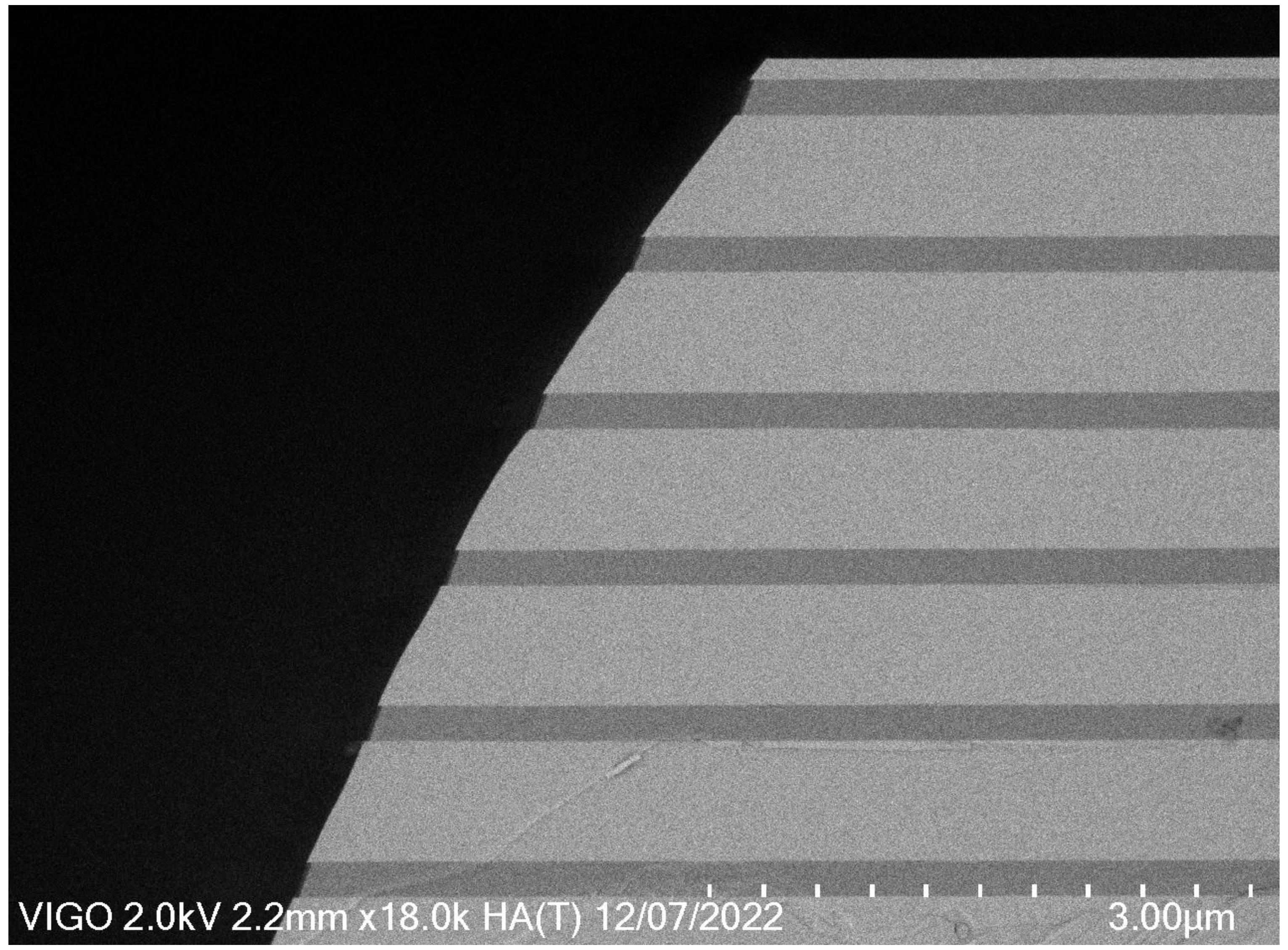
- Absorbers, tunneling junctions, contact and N layers made of InAs/InAsSb SLs
- Bulk wide bandgap layers
- Target: SLs average lattice constant matched to GaSb buffer
- **Two configurations for λ=10.6 µm:**
  - 5x0.6 µm-thick absorbers for 300 K
  - 3x0.6 µm-thick absorbers for 200 K

LWIR InAs/InAsSb SL cascade detectors – fabrication



Curvature monitoring during the growth



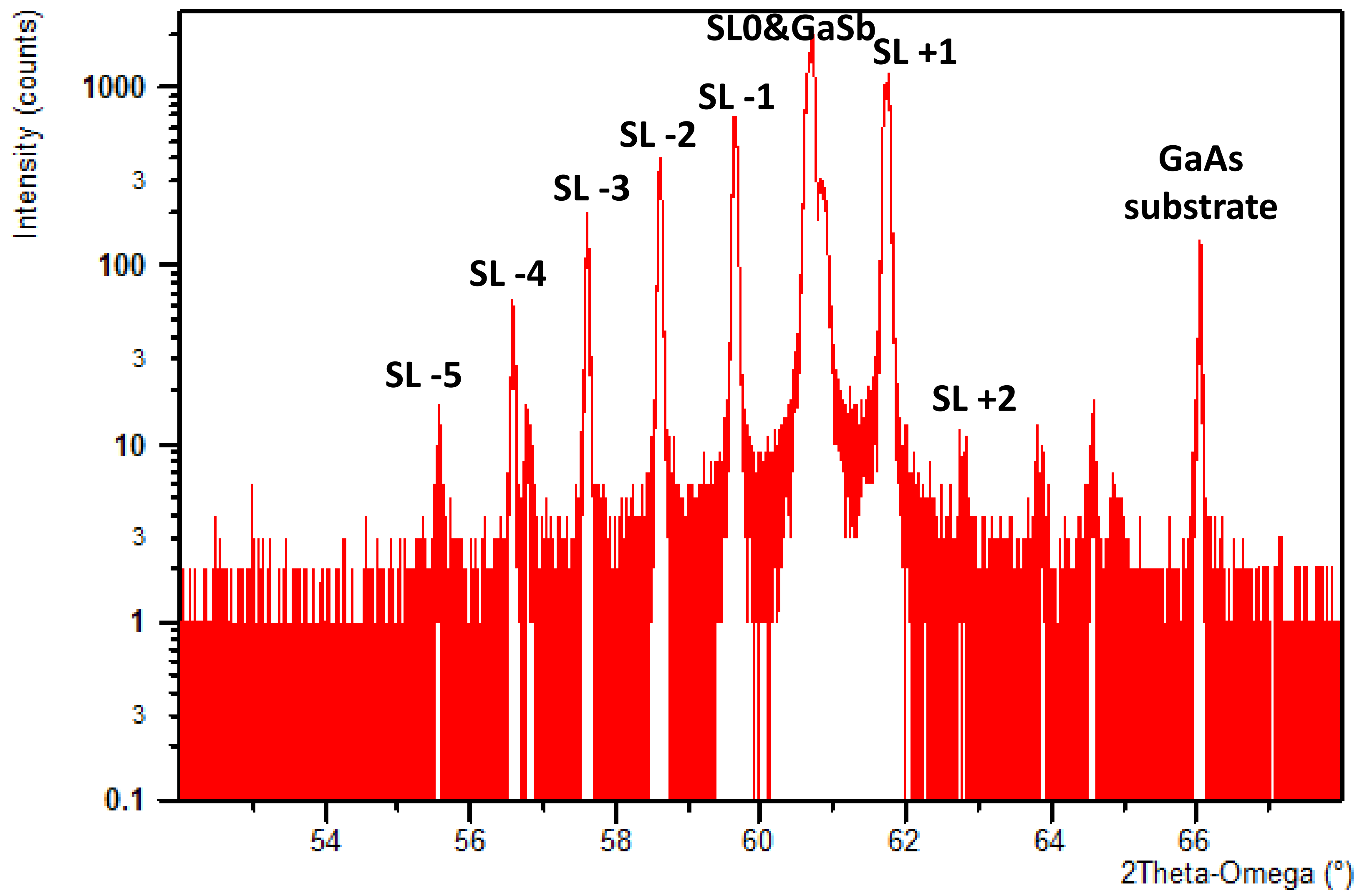


Mesa structure – SEM cross-section

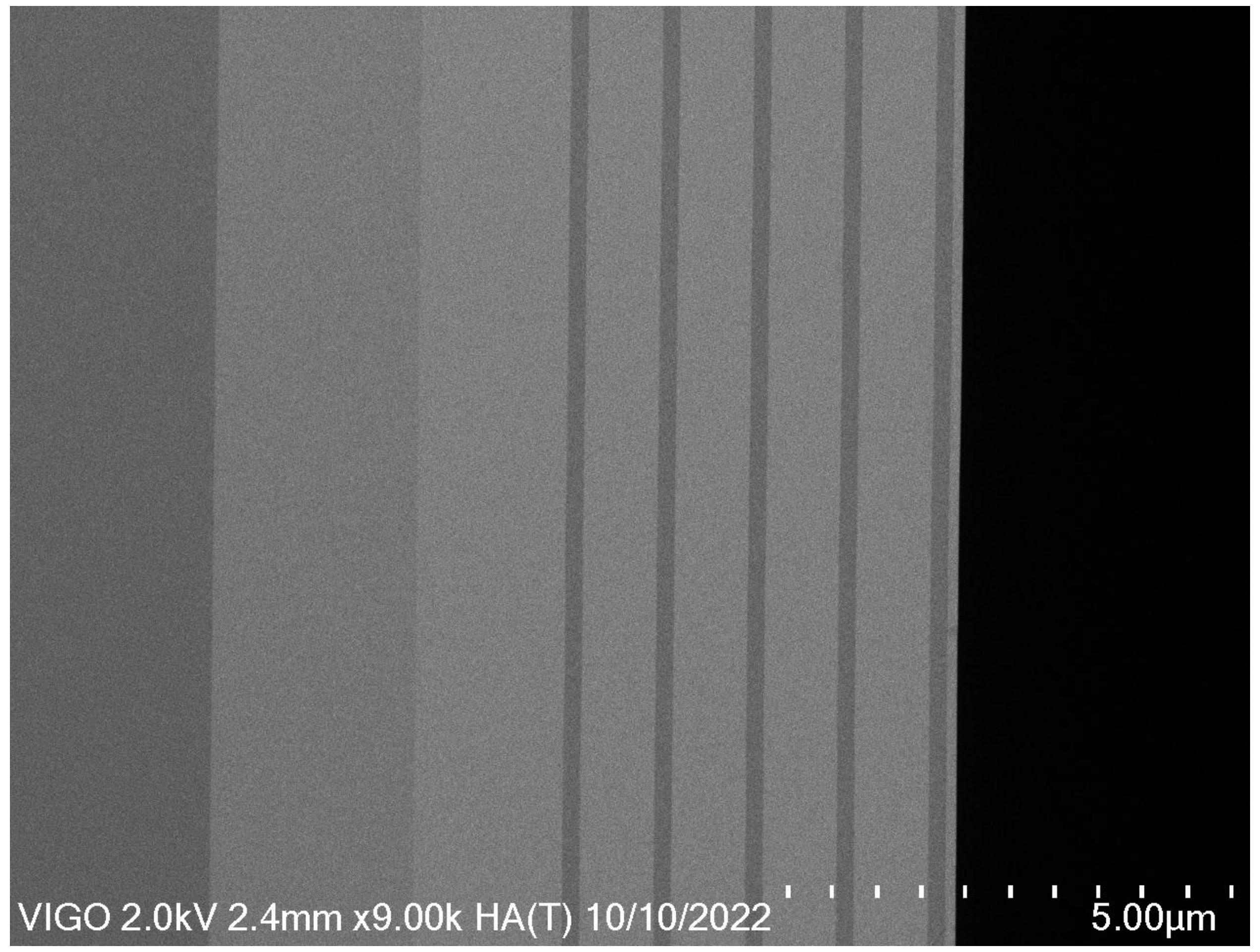
- MBE growth monitored with magnification inferred curvature techinque – Riber *EZ-Curve*
- Wet–etching or ICP-RIE etching of backside illuminated mesa structure photodiodes
- Au metallization
- Physical active area– 100x100 µm^2
- Immersion lenses micromachined from GaAs substrate
- Optical area – 1x1 mm^2

LWIR InAs/InAsSb SL cascade detectors – wafer characterization

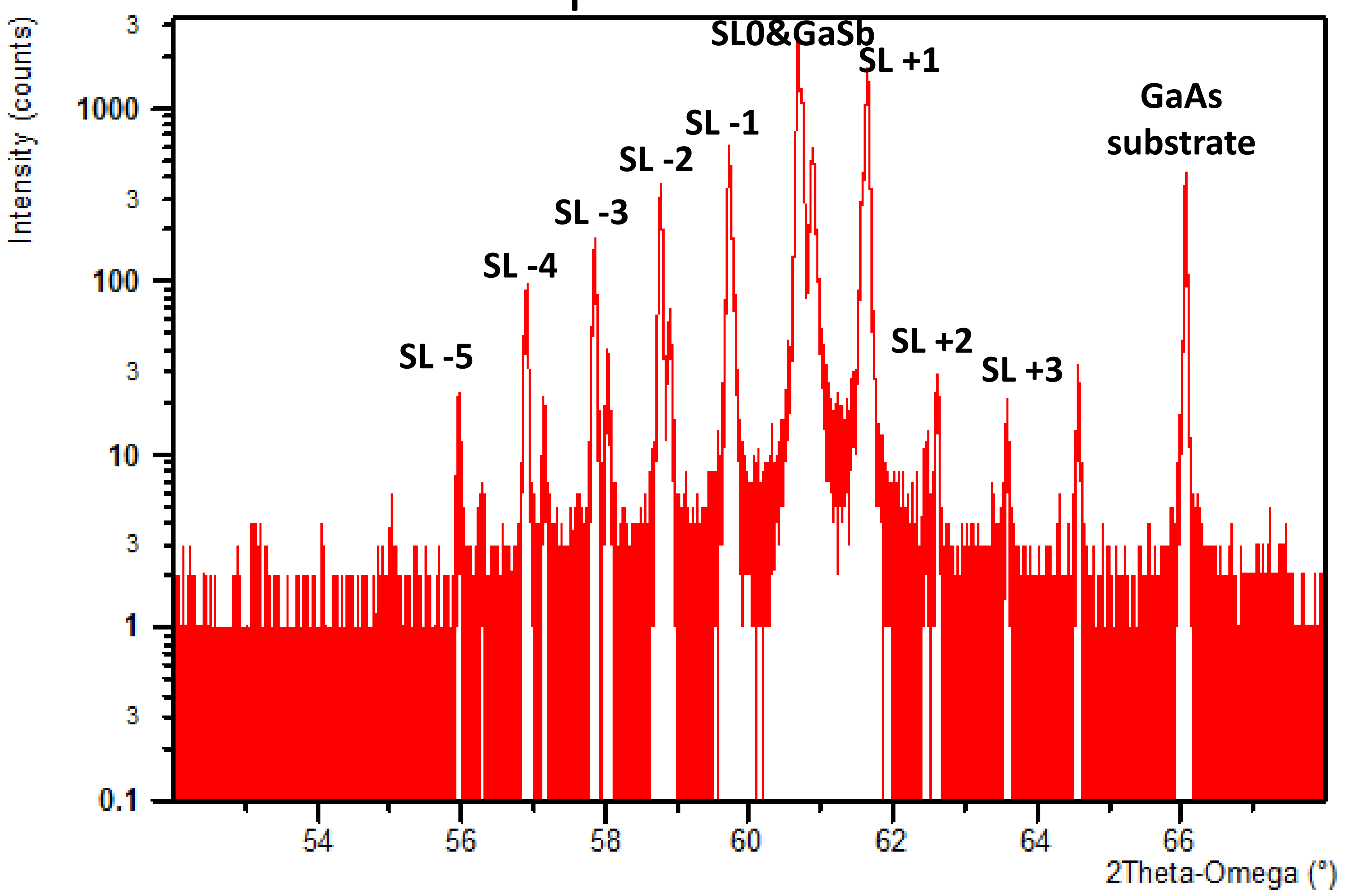
5x0.6 µm architecture



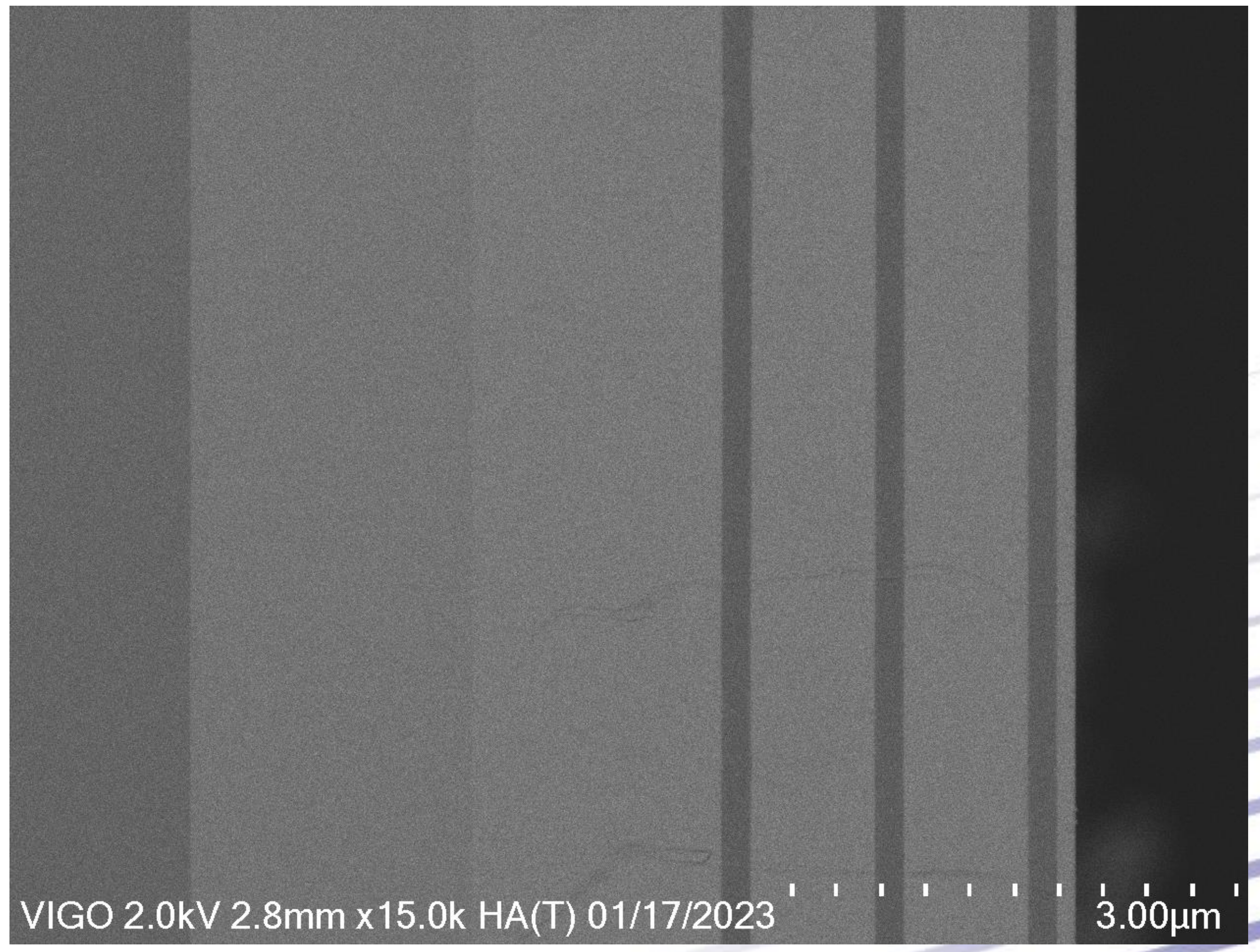
Absorber SL: period=9.83 nm (7.48 nm InAs / 2.35 nm $InAsSb_{0.39}$)



3x0.6 µm architecture



Absorber SL: period: 10.68 nm (8.13 nm InAs / 2.55 nm $InAsSb_{0.395}$)



LWIR InAs/InAsSb SL cascade detectors – I-V curves

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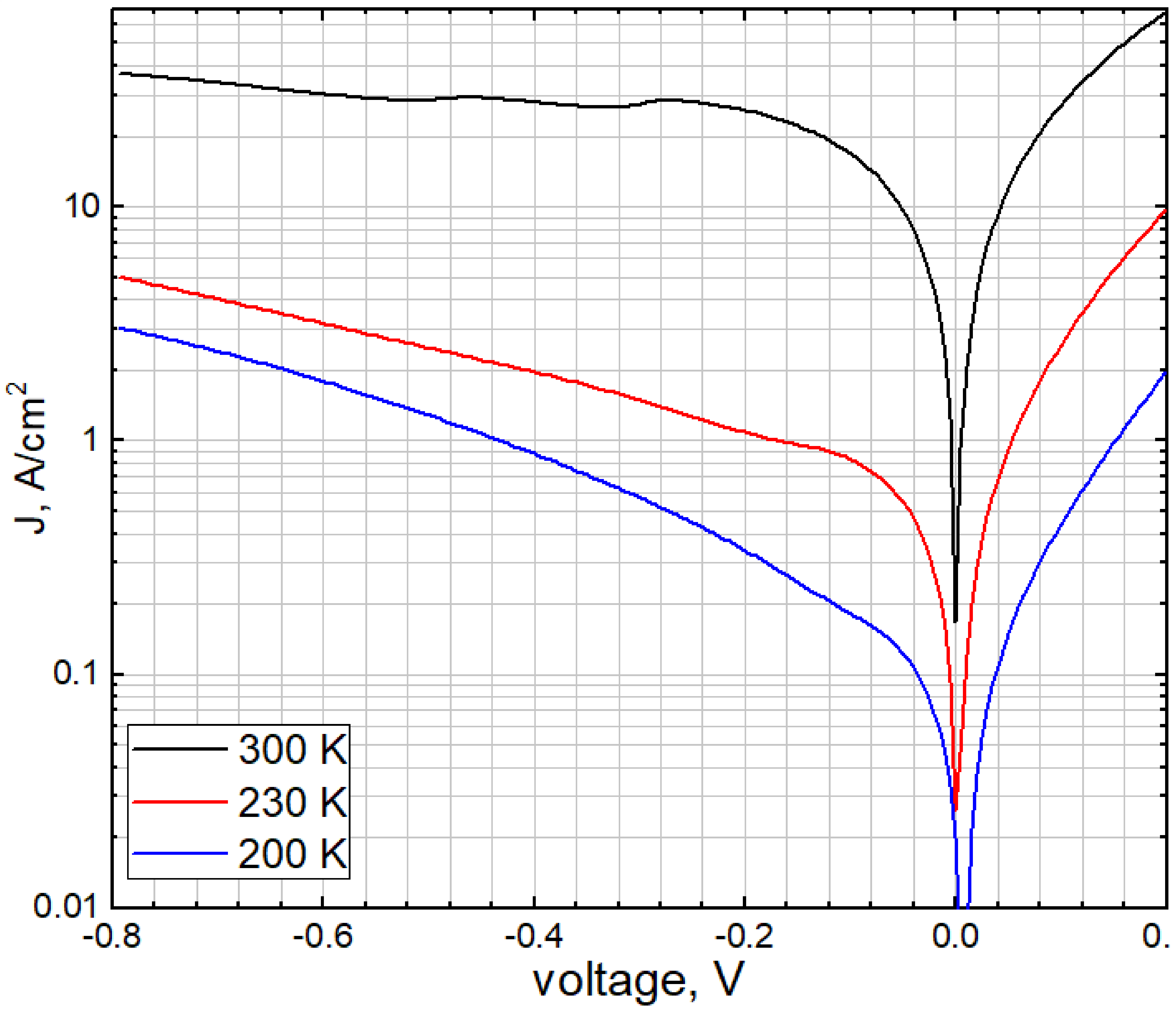
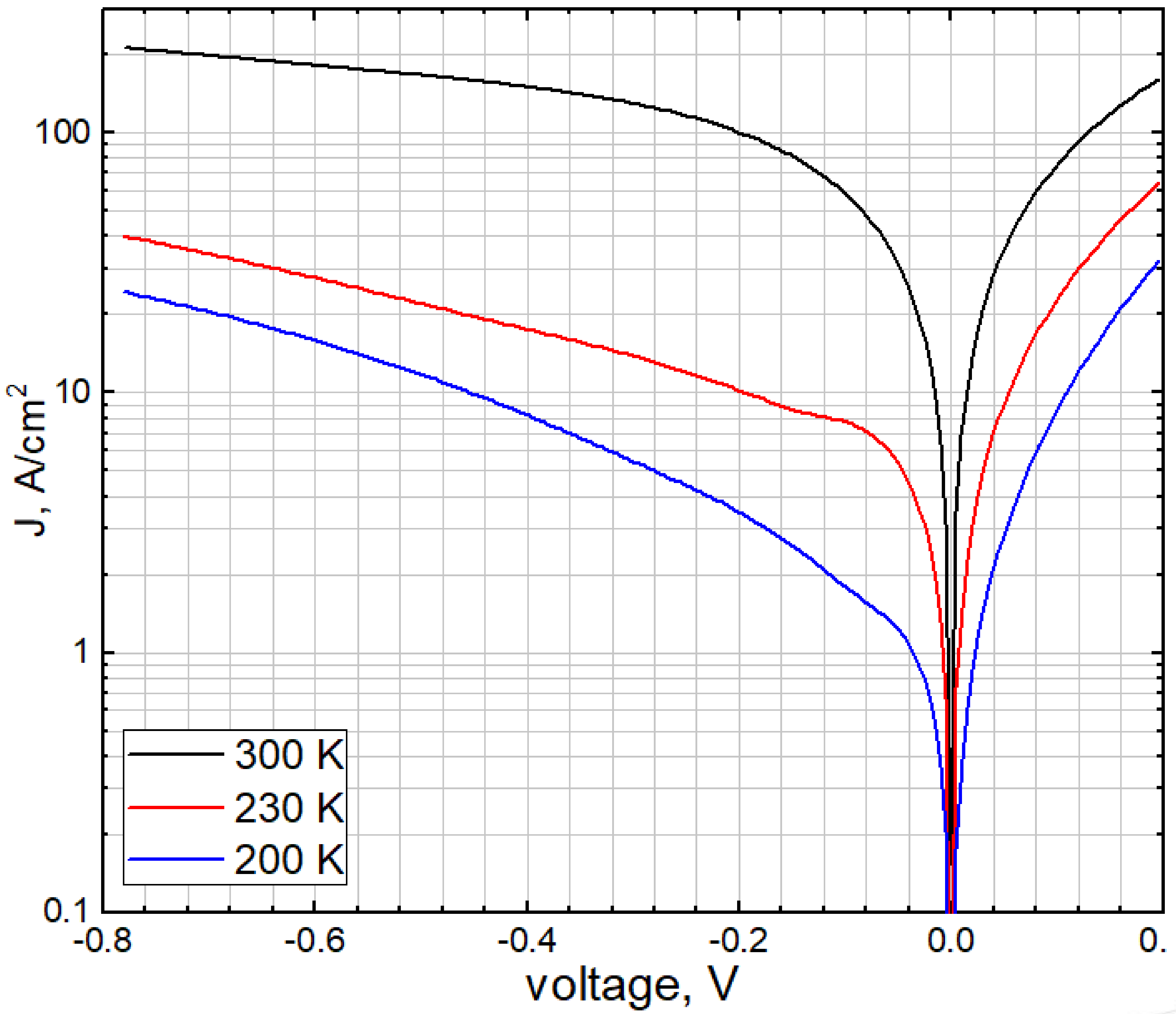
Device for 300 K, λ=10.6 μm (5x0.6 μm)



Device for 200 K, λ=10.6 μm (3x0.6 μm)

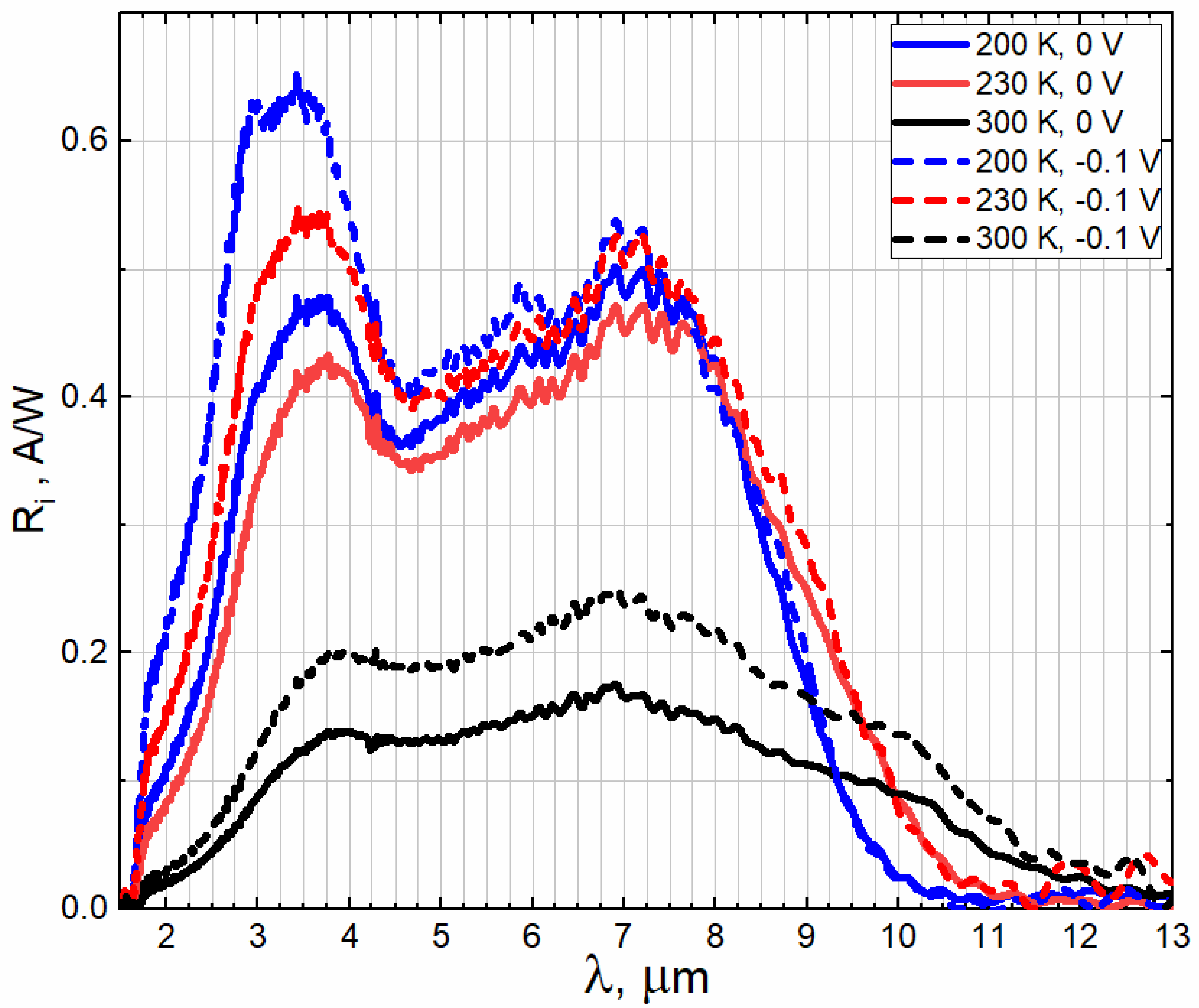


- Saturation of dark current and negative differential resistance features observed only at room temperature
- No saturation visible at lower temperatures due to domination of tunneling and/or SRH related processes in depletion region
- Devices are not optimized for operation with a bias

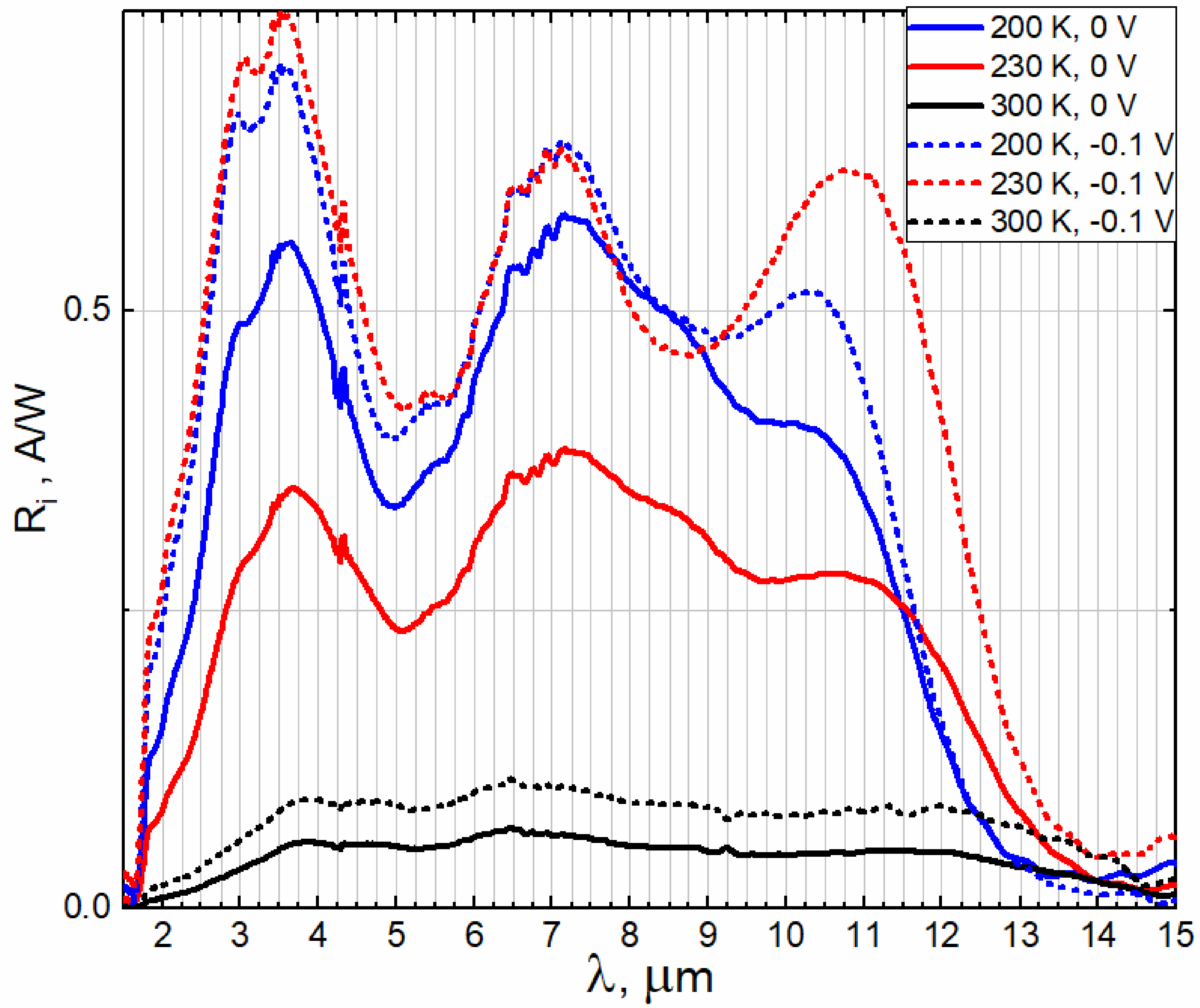
- No saturation of dark current
- Higher dark current than 5x0.6 μm heterostructure due to smaller Eg of absorber and less stages
- Lower series resistance compared to 5x0.6 μm heterostructure

LWIR InAs/InAsSb SL cascade detectors – spectral responsivity

Device for 300 K, λ=10.6 μm (5x0.6 μm)



Device for 200 K, λ=10.6 μm (3x0.6 μm)



- Long wavelength response reduced by a small total thickness of absorbers.
- Low responsivity at 300 K due to relatively high R_s/R_d ratio.
- Optical interference oscillations of spectral response.
- Dependence of responsivity on bias due to parasitic barriers within the heterostructure, e.g. discontinuities in the valence band.

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LWIR InAs/InAsSb SL cascade detectors – spectral detectivity

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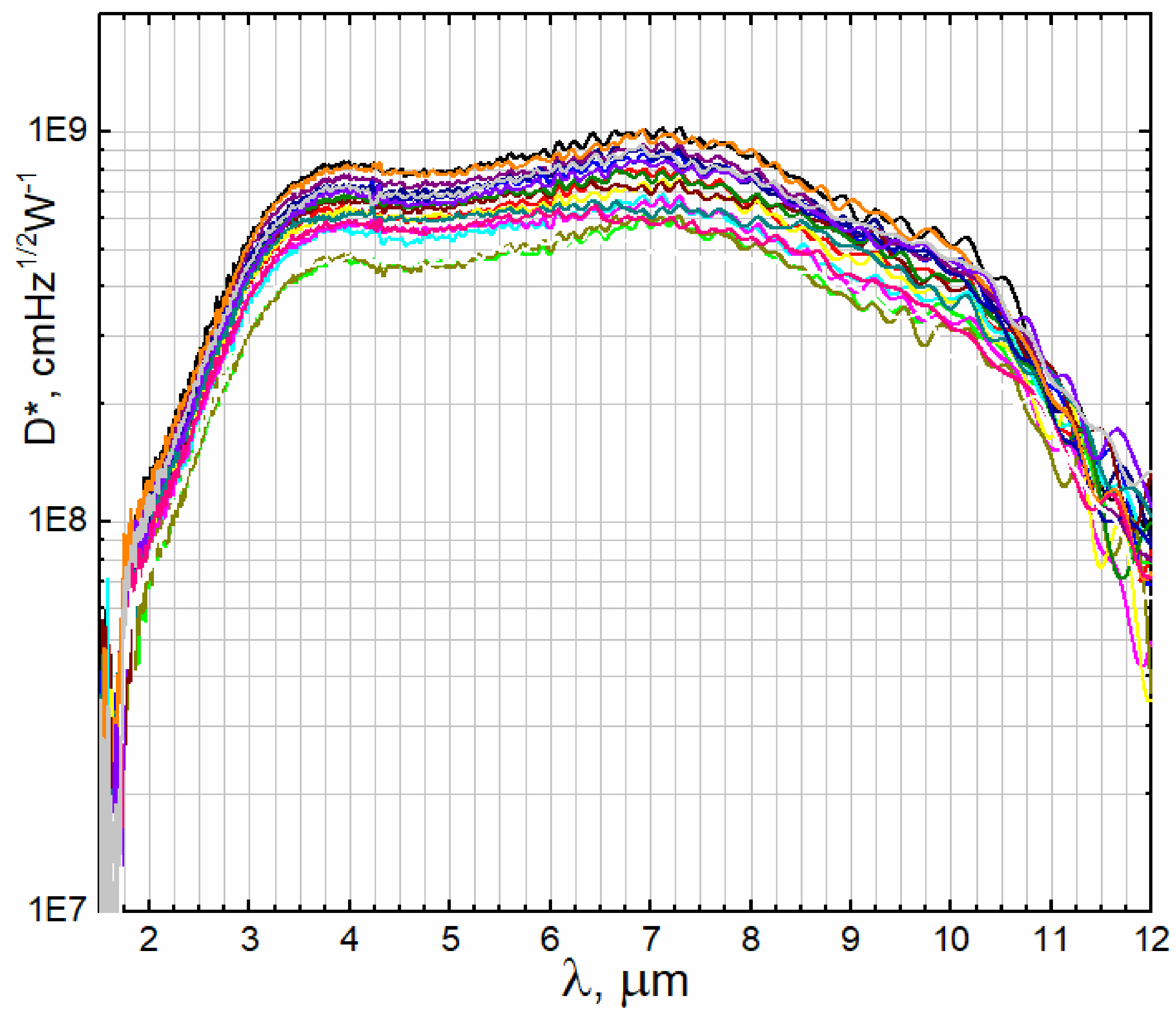
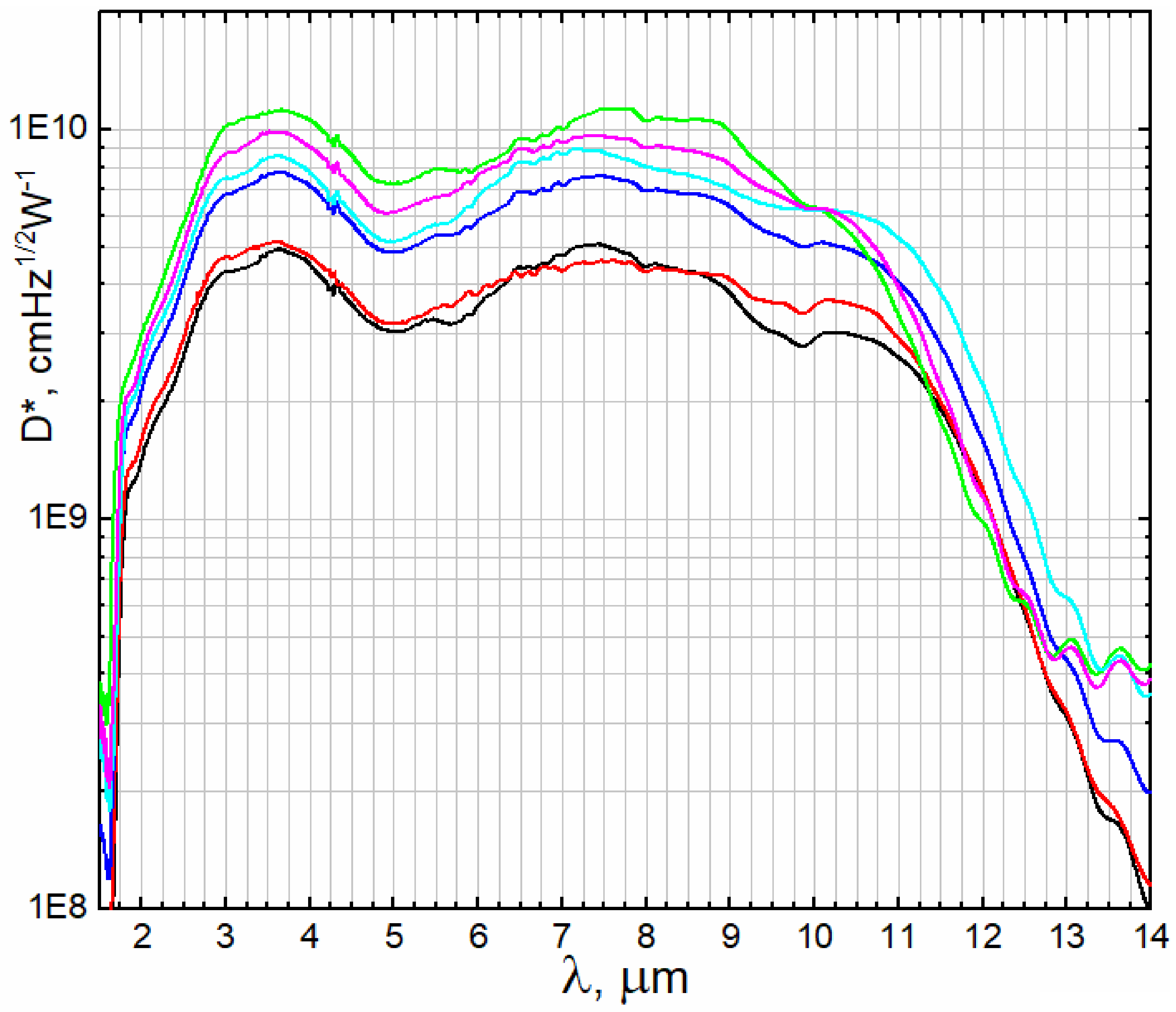
Immersed devices for 300 K, λ=10.6 µm (5x0.6 µm)



Immersed devices for 200 K, λ=10.6 µm (3x0.6 µm)



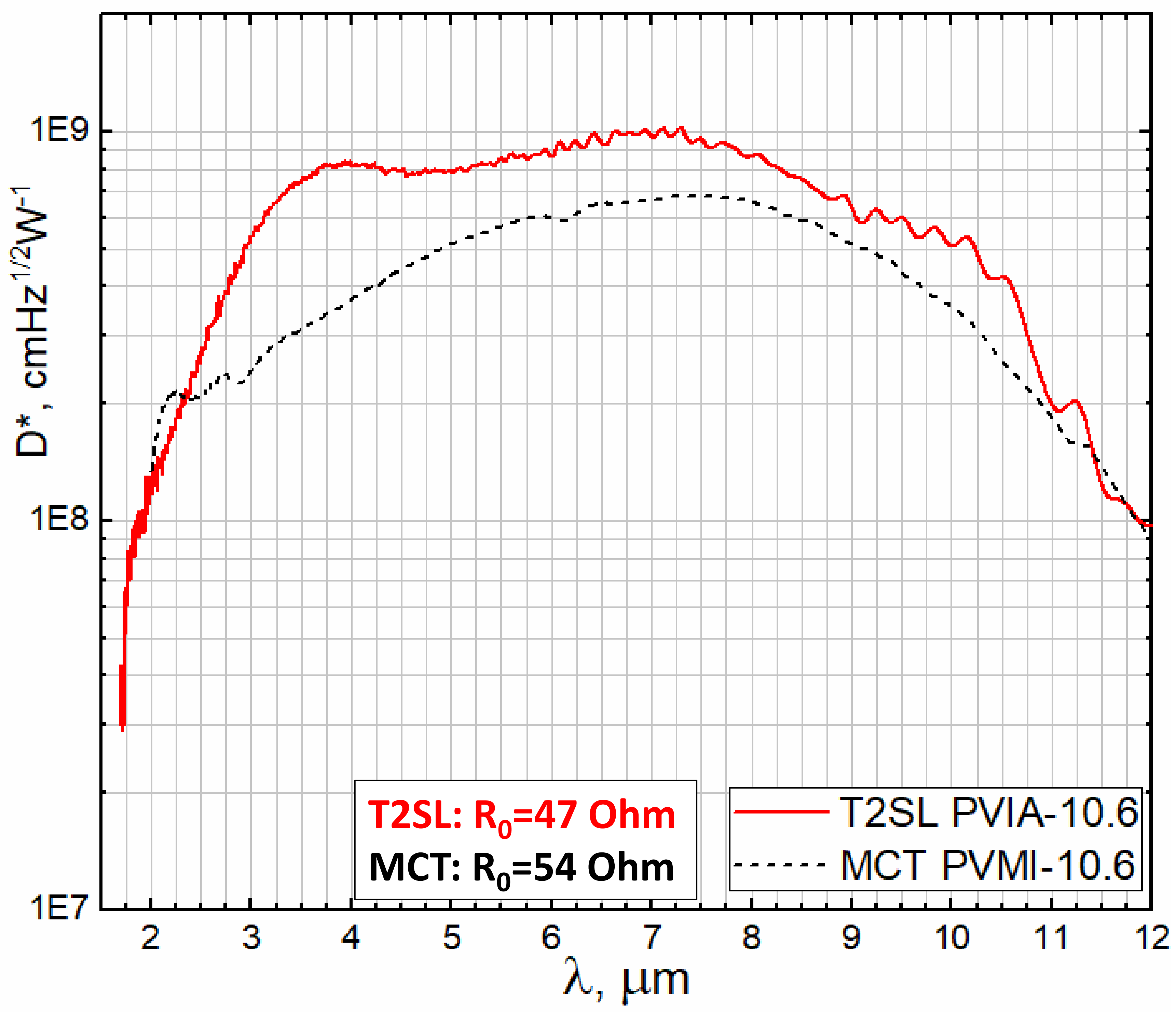
- Backside-illuminated, immersed devices with double-pass of radiation
- Room temperature devices reach ~3x10^8 cm√Hz/W at 10.6 µm, while 200 K devices reach >1x10^9 cm√Hz/W at 10.6 µm
- Detectors used in H2020 EU project „TRIAGE”: *Ultra-broadband infrared gas sensor for pollution detection* in a balanced detection module with digital output

TRIAGE

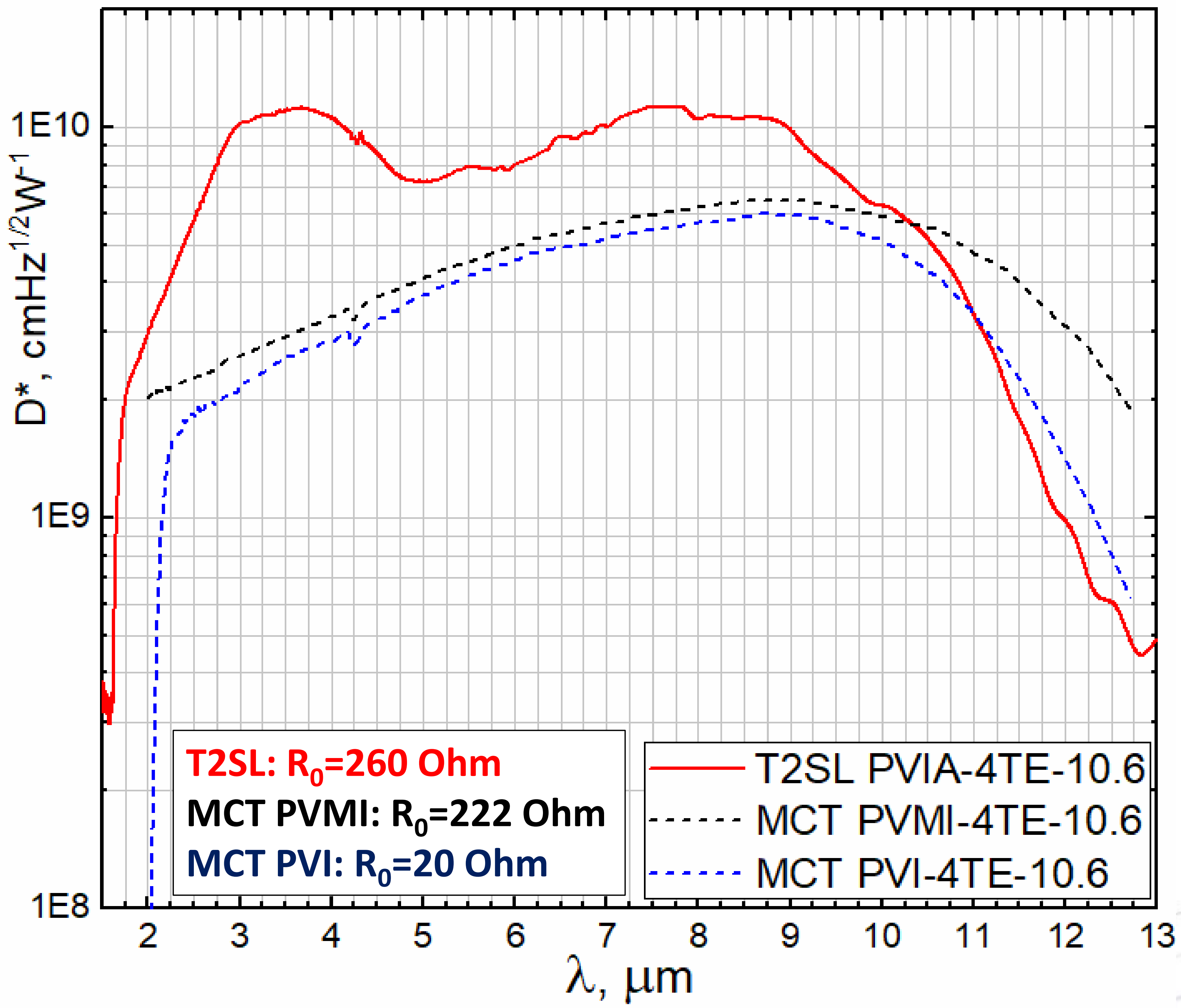
Comparison of parameters with VIGO MCT detectors

VIGO PHOTONICS

Devices for 300 K, λ=10.6 µm (5x0.6 µm)



Devices for 200 K, λ=10.6 µm (3x0.6 µm)



- Detectivity of 200 K and 300 K devices comparable to VIGO MCT PVM and PVI
- Different spectral responsivity shape due to different absorber thickness and absorption coefficient

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Conclusions and outlook

- **The preliminary results of cascade detectors indicate that they can substitute for HOT LWIR MCT in the near future;**
- The cascade devices have a potential for significant improvement of sensitivity;
  - Large number of thinner absorbers is required for near room temperature operation and large area devices;
  - For operation around 200 K, absorbers thicker than 0.6 µm may be optimal;
  - The total thickness of the absorbers should be increased to ~$0.6 \cdot \lambda_{cut\text{-}off}$ in order to improve the long-wavelength detectivity;
  - Tunnel junctions connecting the stages require reduction of absorption losses and elimination of parasitic series resistance;
- HOT devices for 14 µm and longer λ – work in progress.

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