Monday:

Battulga Munkhbat
Klaas-Jan Tielrooij - Optoelectronic, optothermal, and nonlinear photonic applications of 2D quantum materials
Sanshui Xiao - Interlayer exciton in MoS2/WSe2 heterostructures and their potential application for lasing
Inge Asselberghs - Processing 2D-materials in an industrial relevant environment

Tuesday:

Francesco Buatier de Mongeot - Large-area and deterministic nanopatterning of 2D semiconducting layers for flat-optic photon harvesting and nanoelectronics
Yuije Guo - Waveguide-integrated, metasurface-enhanced photodetectors: graphene and beyond
Natalie Vermeulen - Extra-ordinary spectral broadening behavior of laser pulses in graphene-enhanced waveguides
Jason Lynch - 360° Phase Modulation using Exciton-Polaritons in a Two-Dimensional Superlattice
Julien Barrier - High-bias spectroscopy of graphene superlattices and applications for photon detection
Amos Martinez
Giancarlo Soavi - Nonlinear valleytronics in 2D materials
Pedro Soubelet - Electron-Phonon interactions in van der Waals MoSe2/WSe2 Heterobilayers

Wednesday:

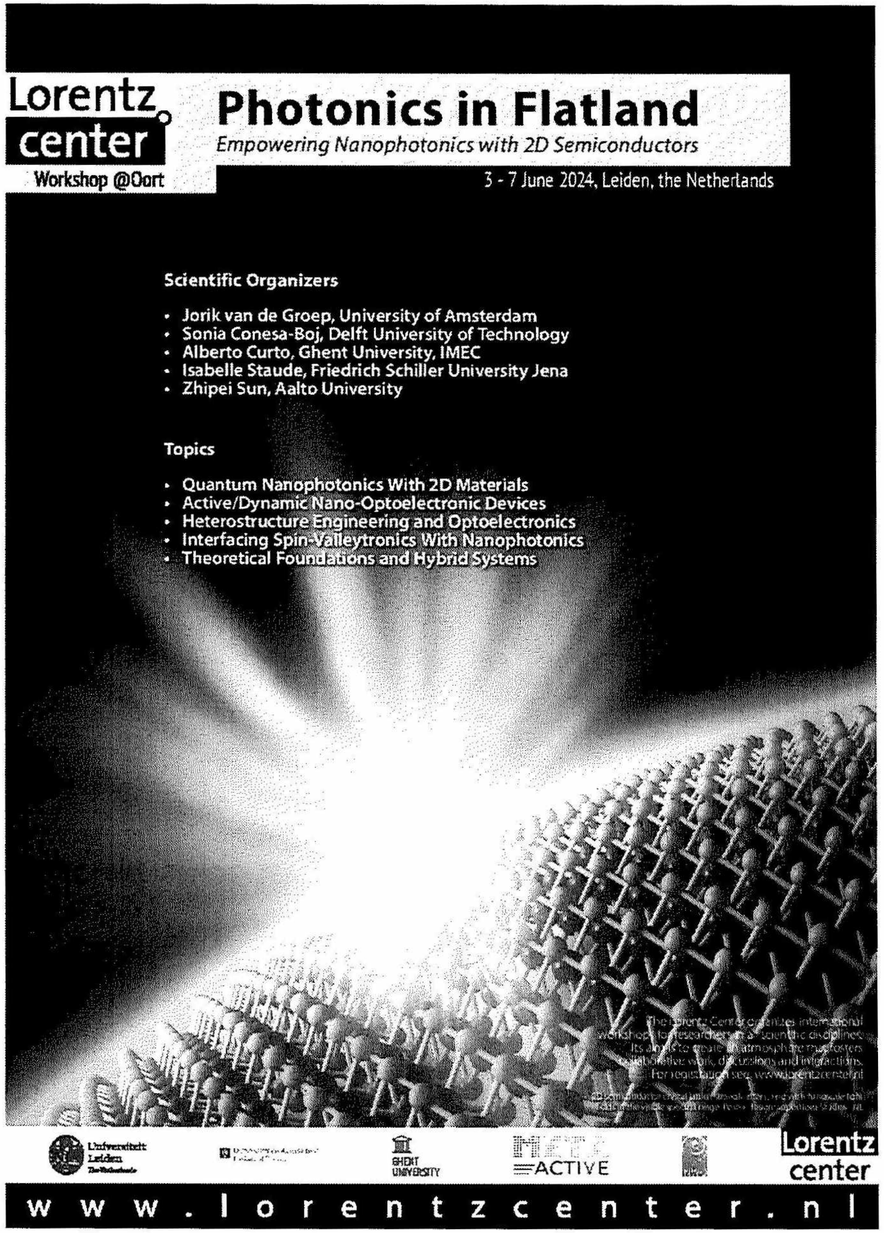
Itai Epstein - Light-exciton Interaction in Semiconducting 2D Materials
Dragomir Neshev - Tunable nonlinear emission from TMDC metasurfaces
Zlata Federova - Advancing optical control of valley excitons in 2D semiconductors
Lara Greten - 2D Semiconductor-Plasmonic Hybrids: Strong Coupling and Exciton Localization
Ilya Goykhman - 2D materials photonic integration for on-chip photodetection and refractive index tuning

Thursday:

Ipshita Datta - Next-Generation Photonic Platforms based on 2D materials
Javier García de Abajo - Toward efficient excitation of 2D polaritons
Jasper van Wezel - Orbitals, excitons, and chirality in TiSe2.
Abel Brokkelkamp - "Localized Exciton Anatomy and Band Gap Modulation in 1D-MoS2 nanostructures"
Sotirios Papadopoulos - The role of energy transfer in van der Waals light sources and photodetectors
Gius Uddin - Optical Spectrometers with Electrically Tunable van der Waals Junctions
Angela Barreda - Hybrid 2D materials with metallic and dielectric nanostructures
Hai Wang
Xavier Zambrana-Puyalto
Timothy Chester-Parsons - Room temperature strong light-matter interaction in highly anisotropic van der Waals excitonic material $ZrSe_3$

Friday

Kobus Kuipers -Optical twists and valleys in flatland
Peter Christianen - Valley Physics of Excitons in 2D semiconductors probed at High Magnetic Fields
Pratap Chandra Adak
Paul Bouteyre


Lorentz center
Workshop @Oort
Photonics in Flatland
Empowering Nanophotonics with 2D Semiconductors
3 - 7 June 2024, Leiden, the Netherlands
Scientific Organizers
• Jorik van de Groep, University of Amsterdam
• Sonia Conesa-Boj, Delft University of Technology
• Alberto Curto, Ghent University, IMEC
• Isabelle Staude, Friedrich Schiller University Jena
• Zhipei Sun, Aalto University
Topics
• Quantum Nanophotonics With 2D Materials
• Active/Dynamic Nano-Optoelectronic Devices
• Heterostructure Engineering and Optoelectronics
• Interfacing Spin-Valleytronics With Nanophotonics
• Theoretical Foundations and Hybrid Systems
Universiteit Leiden
Ghent University
ACTIVE
Lorentz center
www.lorentzcenter.nl

PHOTONICS RESEARCH GROUP 04-06-2024

WAVEGUIDE-INTEGRATED, METASURFACE-ENHANCED PHOTODETECTORS: GRAPHENE AND BEYOND

Yujie Guo[1], Tom Reep[1], Jons Van Kerrebrouck[2], David Schaubroeck[3], Tom Sistermans[1], Junyi Han[1],
Xin Guo[1], Gunther Roelkens[1], Jons Van Campenhout[4], Alberto G. Curto[1], Dries Van Thourhout[1]

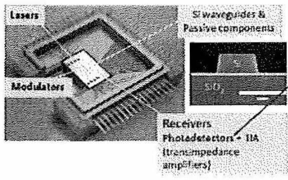
1. Photonics Research Group, Ghent University-imec, Gent, Belgium
2. IDLab, Ghent University-imec, Gent, Belgium
3. Centre for Microsystems Technology, Ghent University-imec, Gent, Belgium
4. imec, Leuven, Belgium

GHENT UNIVERSITY imec embracing a better life

2D MATERIALS FOR INTEGRATED PHOTONICS

Si photonic integrated circuits (PICs)

- Ultra-compact circuits
- CMOS compatibility
- Integration with electronics



2D Materials for PICs

Pros
- Broadband
- Scalability
- Platform compatibility
- Versatility

1. Telecom C-band (1530-1565 nm)
   data communication
2. Mid infrared
   sensing

Challenge
- Atomic thickness
→ limited quantum efficiency

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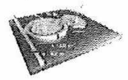
2D-MATERIAL-BASED, WAVEGUIDE-INTEGRATED PHOTODETECTORS

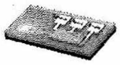
To enhance the quantum efficiency in the optical domain:

- **Optical cavities**

MoTe₂

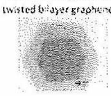


Black phosphorus

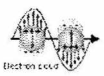


- **van Hove singularities**

twisted bilayer graphene



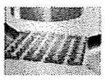
- **Surface plasmon resonance**



Localized surface plasmon resonance
Mie scattering

Metasurface

- Tunable resonance frequency



Bandwidth: >500 GHz
Free-space illumination

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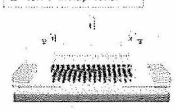
2D-MATERIAL-BASED, WAVEGUIDE-INTEGRATED PHOTODETECTORS

To enhance the quantum efficiency

in the electrical domain:

1. Electrostatic gating:
   - Fermi-level tuning
   - carrier multiplication



MoTe₂ Split-gated photodetectors

2. Charge carrier transfer

via material selection:

Graphene

Multi-layer tellurium (Tellurene)

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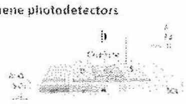
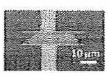
WAVEGUIDE-INTEGRATED, METASURFACE-ENHANCED PHOTODETECTORS: GRAPHENE AND BEYOND

- Metasurface-enhanced, waveguide-integrated graphene photodetectors
  - Device concept & fabrication
  - Performance & mechanisms



- **Waveguide-integrated multilayer-tellurium photodetectors**
  - Synthesis & free-space photodetector
  - Waveguide-integrated photodetector



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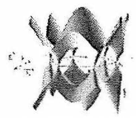
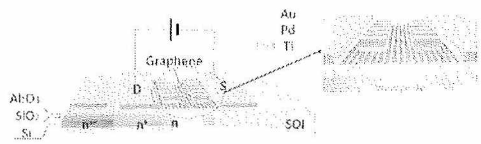
METASURFACE-ENHANCED, WAVEGUIDE-INTEGRATED GRAPHENE PHOTODETECTORS

Monolayer graphene



Dirac cones at vertices of Brillouin zone



- Plasmonic metasurface
  - Near-field enhancement
  - Hot carrier transfer
  - Resonance frequency tunability
- Local p-i-n junction
  - Efficient carrier separation
- Electrostatic gating from doped waveguide
  - Carrier multiplication
  - Tailoring optoelectronic effects

Enhance responsivity without sacrificing bandwidth

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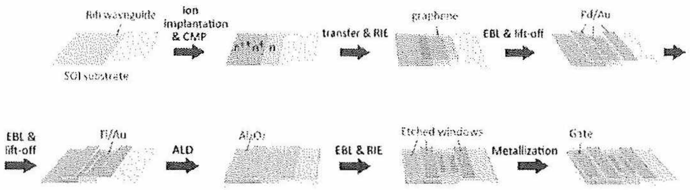
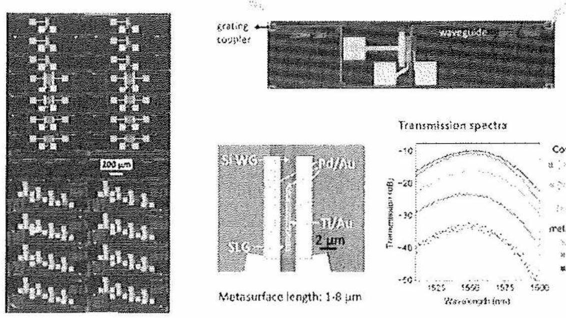
Device Fabrication

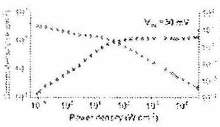


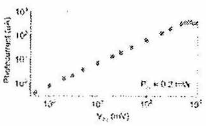
Device Fabrication



Telecom C-band Photoresponse

At Steady state, λ = 1550 nm





- ☐ **High responsivity**

  $R = |I_{ph}|/P_{in}$

  >2 A/W up to 111 W cm⁻²

- ☐ **High photocurrent**

  I_{ph} > 800 µA

- ☐ **High sensitivity**

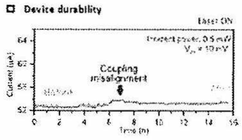
  Optical sensitivity @ 14 nW

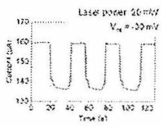
  Noise equivalent power

  $NEP = i_{noise}/R$

  $= 21.95\ pW/\sqrt{Hz}$

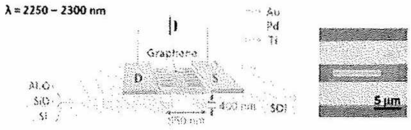
- ☐ **Device durability**

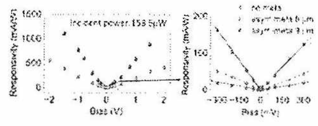


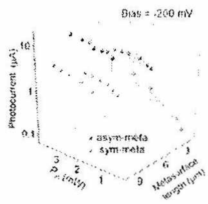


Mid-infrared Photoresponse

λ = 2250 – 2300 nm





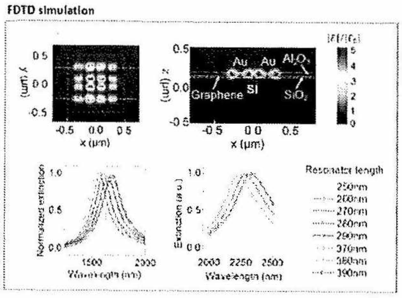


- ☐ **Responsivity:** R_{max} = 3.08 A/W
- ☐ **Photocurrent:** $I_{ph,max}$ > 180 µA

Operation principles

- ☐ Surface plasmon resonance
  - Near-field enhancement
  - Dipolar resonance
  - Tunable resonance

FDTD simulation



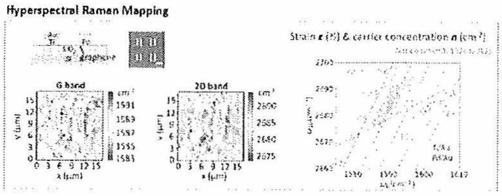
Operation principles

- ☐ Local p-i-n junction

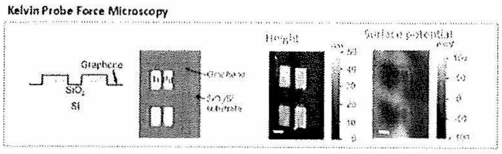
  Charge transfer from metals

  → Graphene Fermi-level shifting

Hyperspectral Raman Mapping



Kelvin Probe Force Microscopy

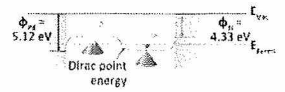


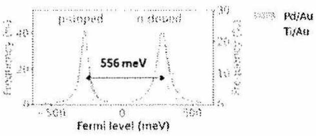
Operation principles

- Local p-i-n junction

Charge transfer from metals
→ Graphene Fermi-level shifting

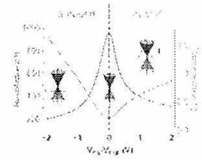
$$E_F = \hbar v_F \sqrt{\pi n}$$





Operation principles

- Electrostatic gating



$R_{total} = 2R_{contact} + \frac{L}{W\sigma}$

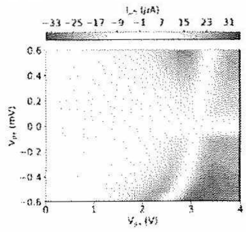
$C_{gate} = \frac{\varepsilon_0 \varepsilon_{SiO_2}}{d_{SiO_2}}$

$\sigma = q\mu\sqrt{n_0^2 + n^{*2}}$

contact resistivity
$R_{contact}$ = 424.56 Ω · μm

carrier mobility:
μ = 6377 cm²/V·s

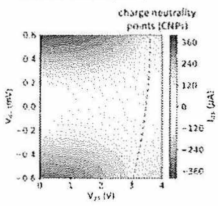
Synergy of different optoelectronic effects



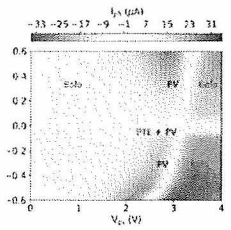
Define a positive current flowing from the source to the drain

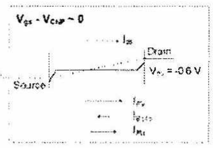
Operation principles

Transfer curves (dark)



Photocurrent mapping



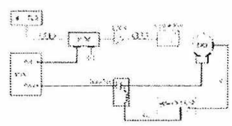


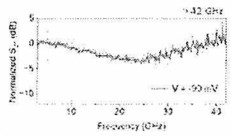
Freitag, M. et al. Nature Photon 7, 53–59 (2013)

Telecommunication C-band photoresponse

At High Frequency

- Bandwidth

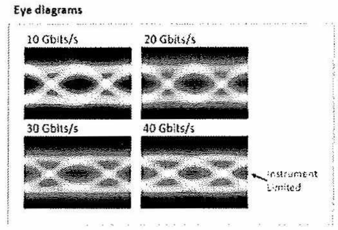




Not limited by carrier transit time and RC constant

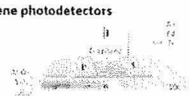
Data communication

Eye diagrams

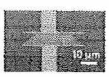


Waveguide-integrated, metasurface-enhanced photodetectors: graphene and beyond

- **Metasurface-enhanced, waveguide-integrated graphene photodetectors**
  - Device concept & fabrication
  - Performance & mechanisms



- Waveguide-integrated multilayer-tellurium Photodetectors
  - Synthesis & free-space photodetector
  - Waveguide-integrated photodetector

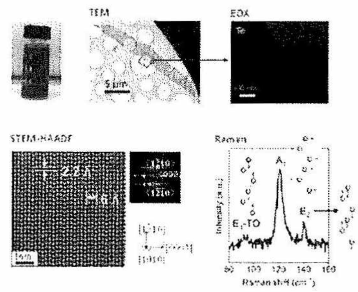


Multilayer-tellurium (Tellurene)

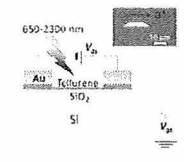
Tellurene for MIR photodetectors

- p-type semiconductor: 0.35–1.2 eV
- Strong absorptance
- High mobility μ_{2D} = 700 cm²V⁻¹s⁻¹
- Long-term ambient stability

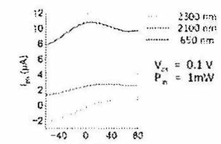
Hydrothermal synthesis



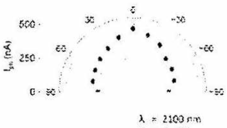
Broadband Multilayer-Tellurium Photodetectors



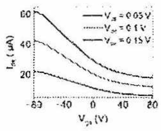
□ Wavelength-dependent photoresponse



□ Polarization-resolved photoresponse



□ P-type transfer characteristics



Optical transition:

- indirect band gap at **0.31 eV** (4000 nm)
- direct band gap at **0.71 eV** (1746 nm)

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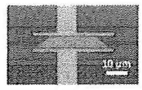
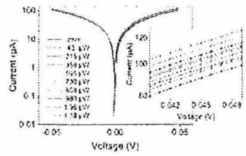
Waveguide-Integrated Multilayer-Tellurium-Based Photodetectors

@ 2300 nm

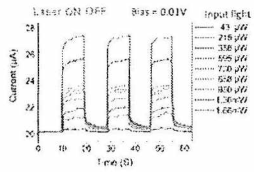


I-V curves

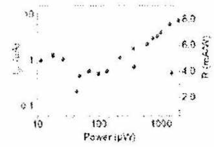


R_{ext} = 0.3 A/W @ V_{ds} = 0.5 V

Time-resolved photoresponse



Linear dynamic region



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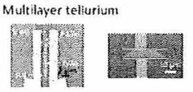
Conclusion

2D-material-based photodetectors for PICs

Materials:
- Monolayer graphene
- Multilayer tellurium

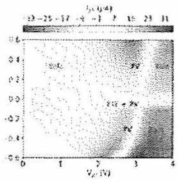


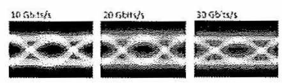
Plasmonic metasurfaces:
- Near-filed enhancement
- Tunable resonance frequency

Carrier extraction & multiplication:
- Electrostatic gating
- Charge carrier transfer

Enhance photoresponsivity without sacrificing bandwidth

- □ High responsivity
- □ High sensitivity
- □ High robustness
- □ High bandwidth





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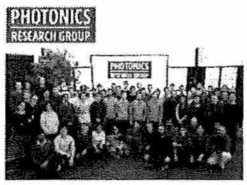
Acknowledgements



Tom Reep
Tom Sistermans
Junyi Han
Xin Guo
Gunther Roelkens
Alberto G. Curto
Dries Van Thourhout

Joris Van Campenhout

IDLab

Joris Van Kerrebrouck
Nishant Singh

CMST

David Schaubroeck

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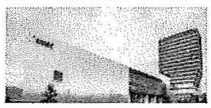

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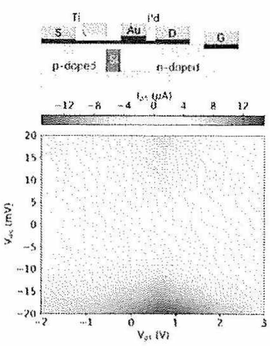

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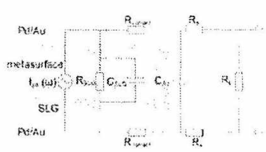
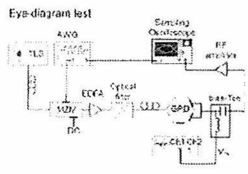


Eye-diagram test



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