Istituto Nazionale di Fisica Nucleare
Sezione di PISA

NANO-SWIR
NANOscale materials for next-generation SWIR hyperspectral sensors

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Responsabile locale Pavia: Vittorio Bellani
Responsabile nazionale: Franco Spinella, INFN Pisa

Nuova proposta 2026

NANO-SWIR

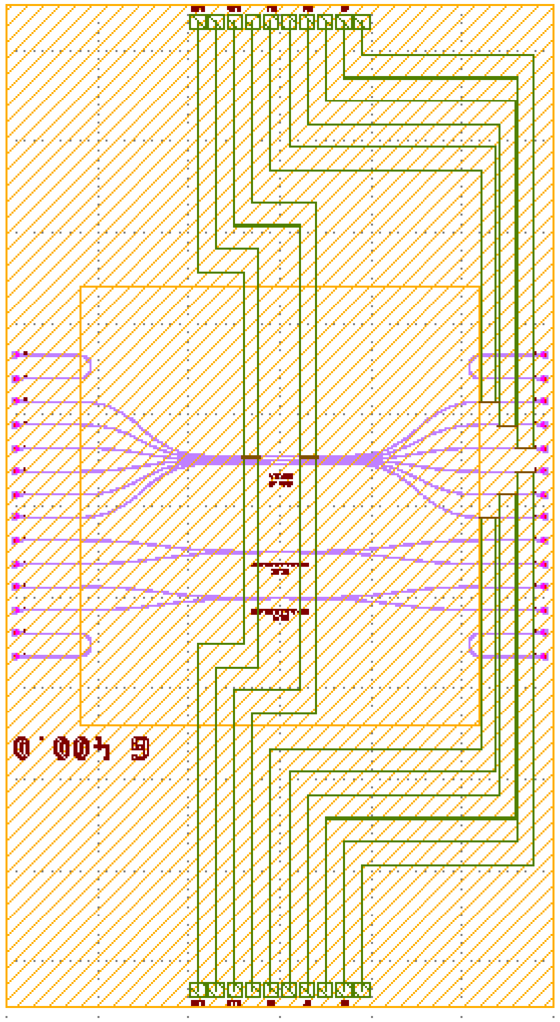
- Sviluppo di matrici di sensori in banda SWIR-MWIR (1 – 8 um) ad altissima sensibilità tramite materiali innovativi.
- 3 Sezioni coinvolte: PI, PV, RM2
- Know-how da QUANTEP, PNRR-NQSTI
- Possibili utilizzi:
  - Medicale
  - Astronomia IR
  - Agricoltura di precisione (satelliti, droni)
  - Sicurezza

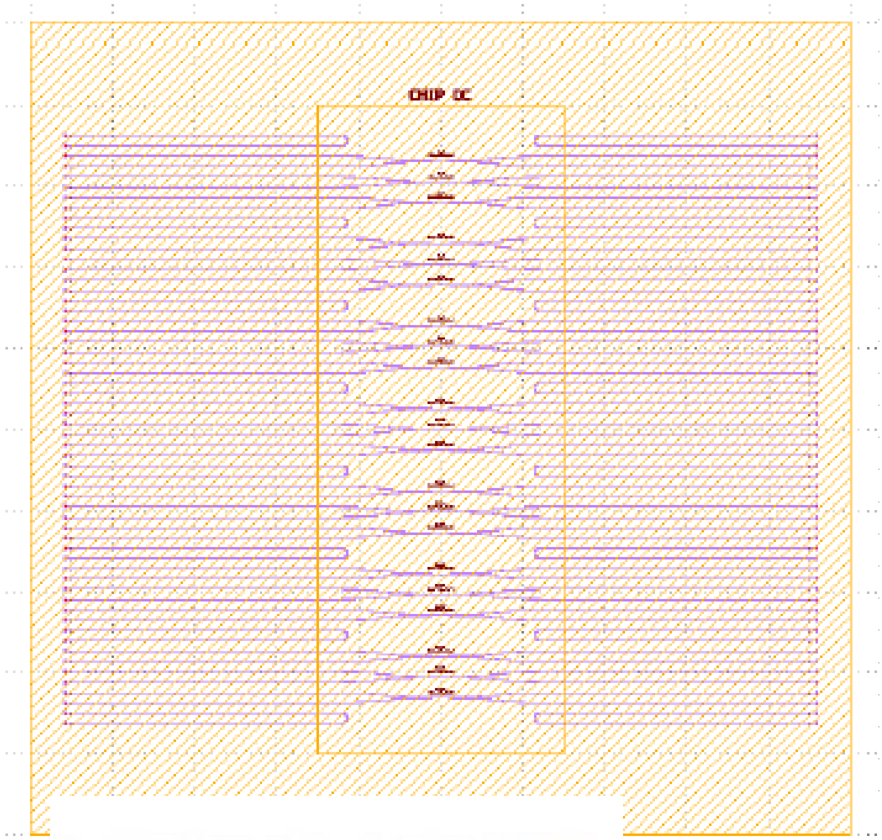
Sigla in corso: QUANTEP

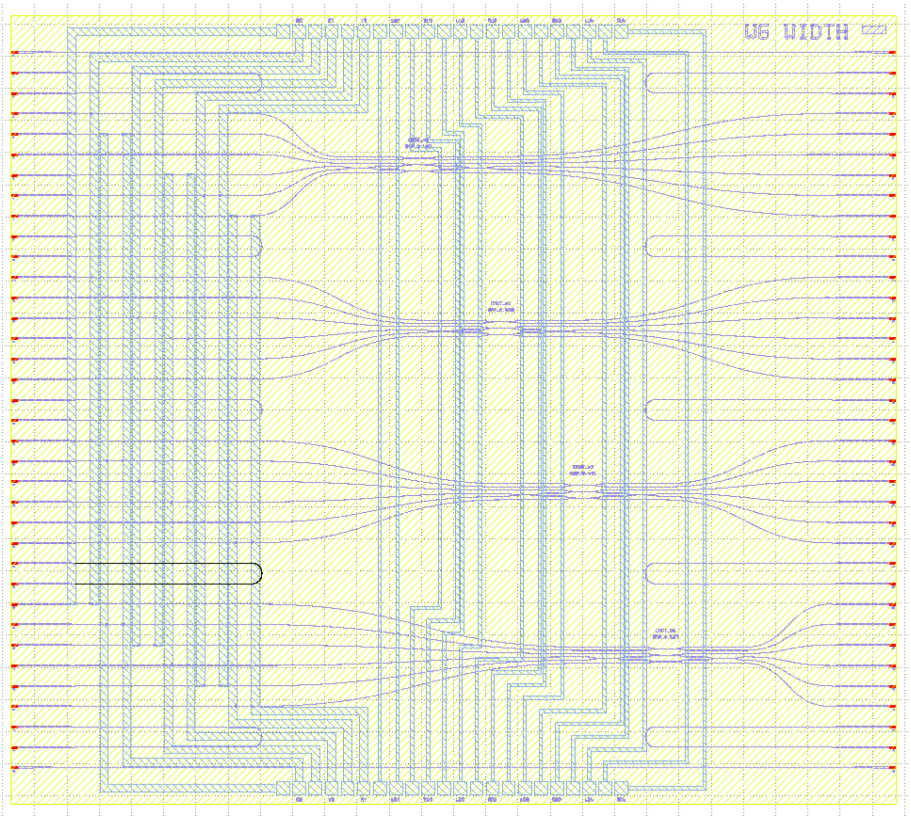
- Chiude a fine 2025
- 2 linee di ricerca:
  - Sviluppo di circuiti in silicon-photonics per Quantum Computing
  - Rivelatori/generatori di singolo fotone, eventualmente integrati

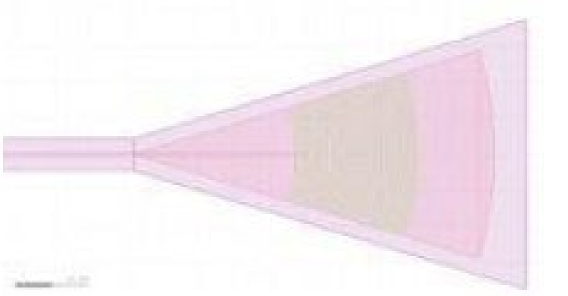
QUANTEP: silicon photonics

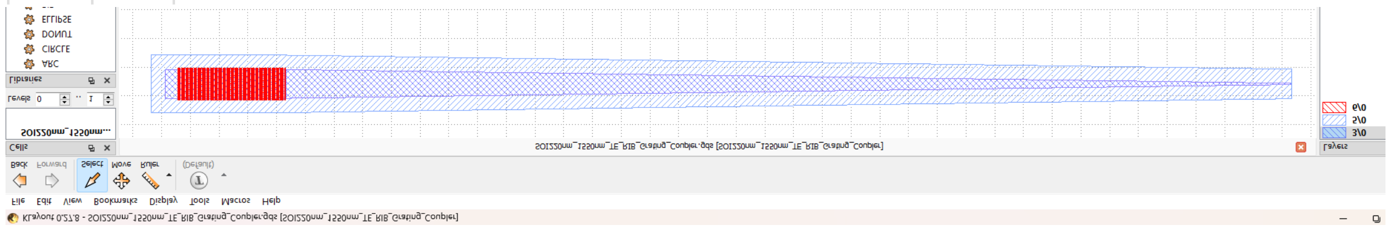
- Progetto & simulazione di vari circuiti fotonici tramite Ansys Lumerical & Luceda Photonics

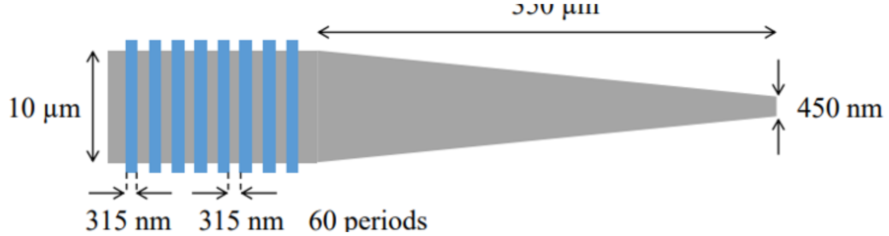




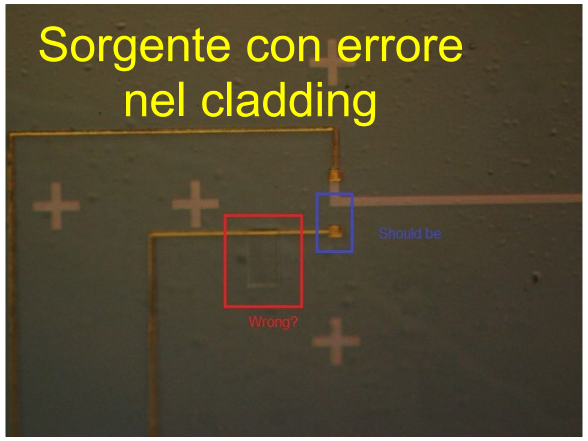


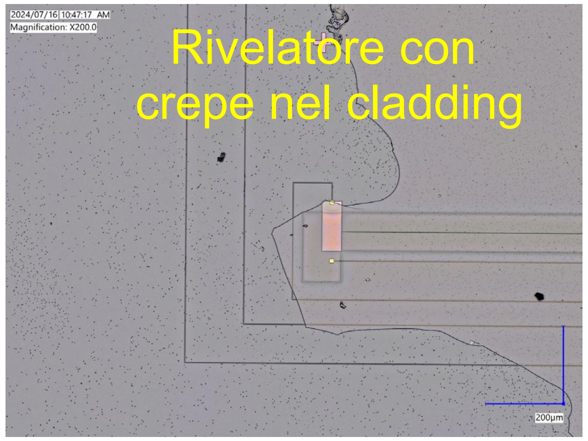


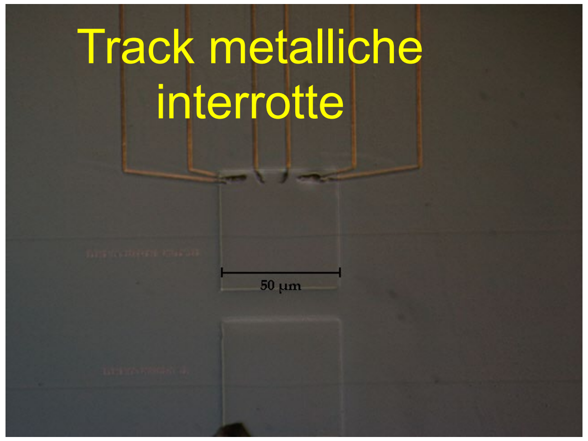


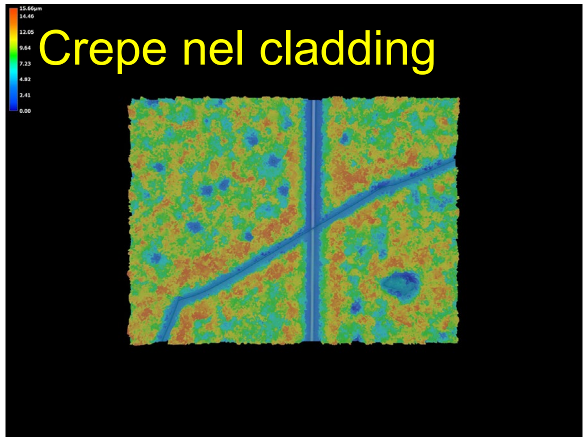

10 µm
450 nm
315 nm
315 nm
60 periods

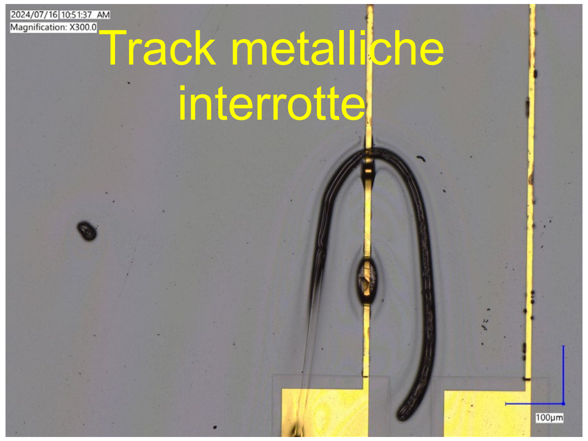
QUANTEP: fonderie

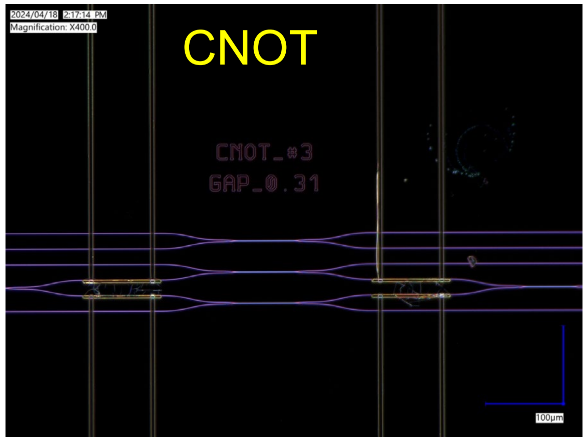

Sorgente con errore nel cladding
Should be
Wrong?


Rivelatore con crepe nel cladding


Track metalliche interrotte

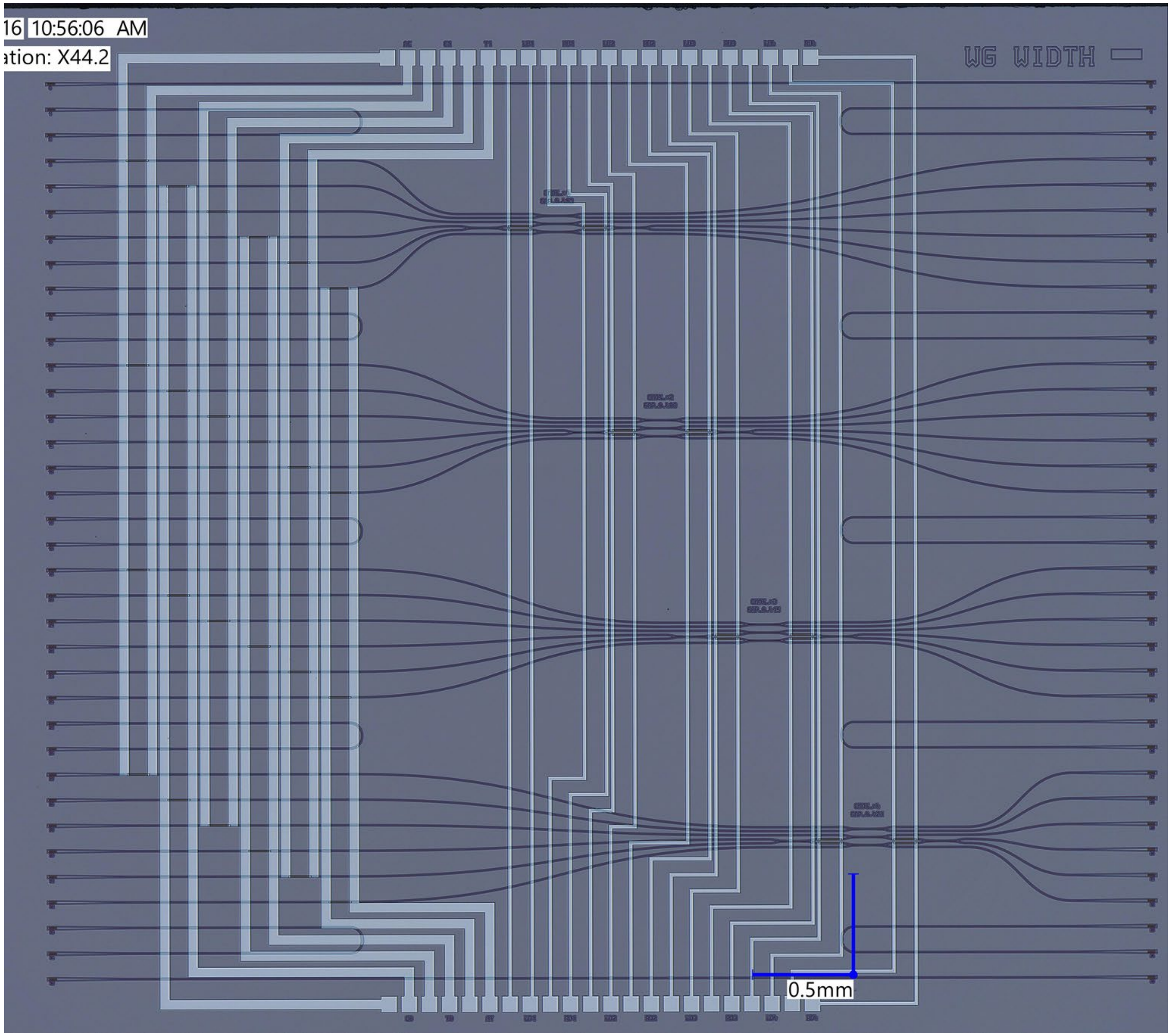

Crepe nel cladding


Track metalliche interrotte


CNOT
CNOT_03
GAP_0.31
100μm

- Problemi di produzione & lunghissimi tempi di consegna: poco compatibile con progetti INFN di durata limitata …
- Costi molto elevati …

QUANTEP: Cornerstone


16 10:56:06 AM
ation: X44.2
WG WIDTH
0.5mm

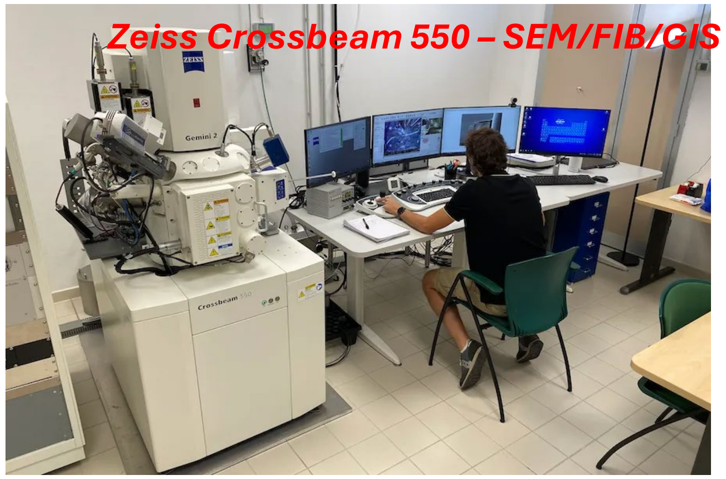
CORNERSTONE

UKRI Engineering and Physical Sciences Research Council

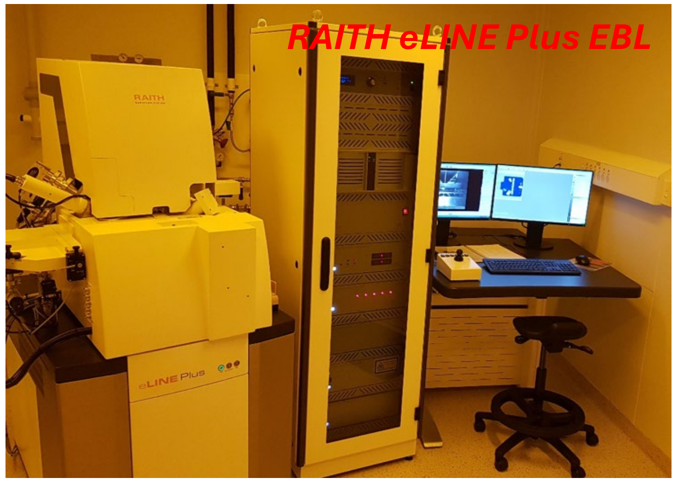
- Prototipo OK (4/2025 …)
- Molto costoso
- Testato in regime classico OK
- Test single photon in corso a RM2

Fabbricazione in-house

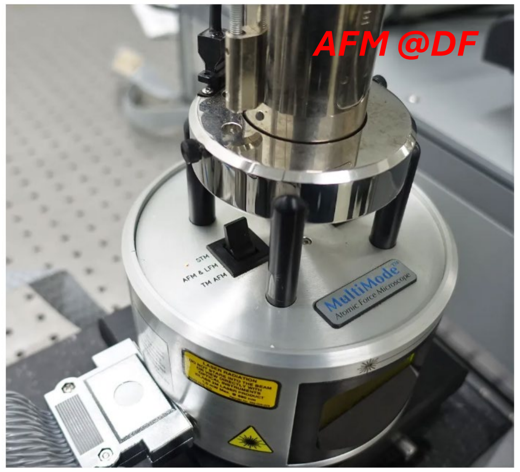
- Dip. Ingegneria (Prof. Pennelli)
- Clean room wet @ INFN-Pisa
  - Acquistate RIE & PE-CVD @ INFN-Pisa & consumabili (QUANTEP,PNRR NQSTI 4-6, aiuto dalla Sezione …)
- Dipartimento, CISUP



Zeiss Crossbeam 550 – SEM/FIB/GIS



RAITH eLINE Plus EBL



AFM @DF

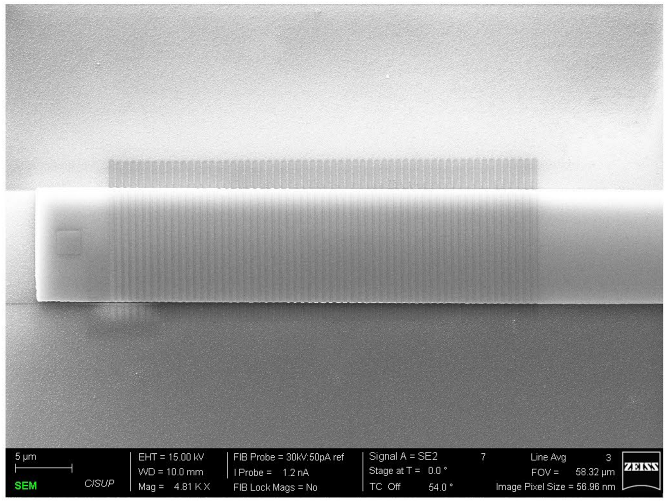
FALCON RIE

Gambetti
FALCON plasma RIE
Gambetti
FALCON plasma RIE

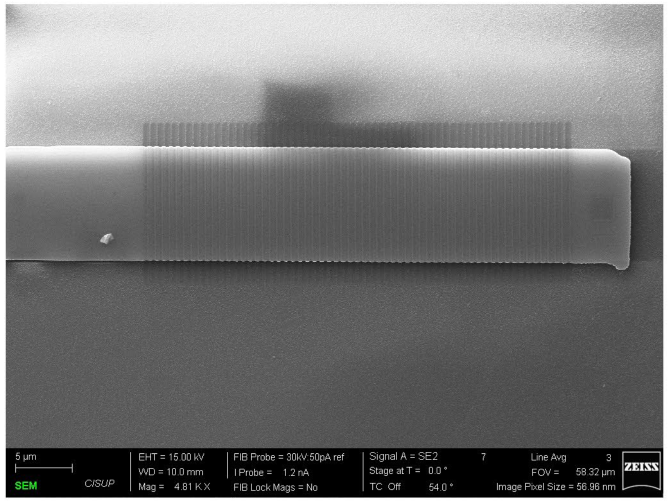
AFM @DII

PE-CVD

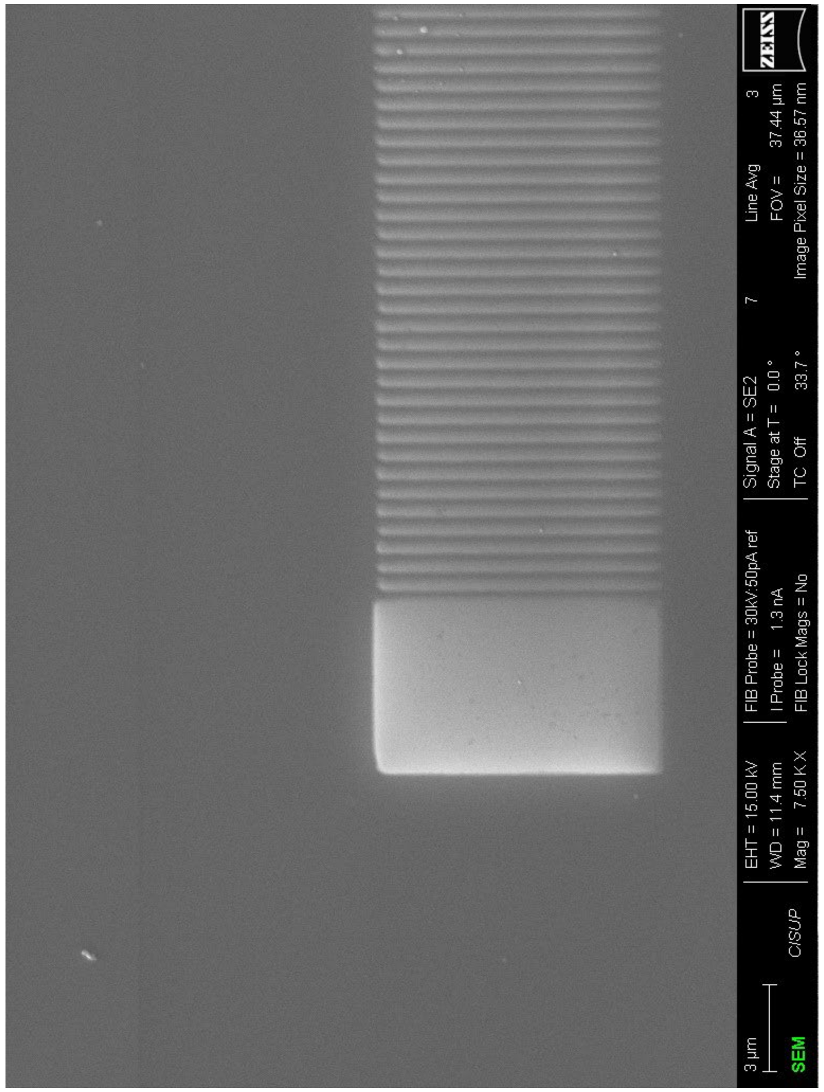
Strutture prodotte

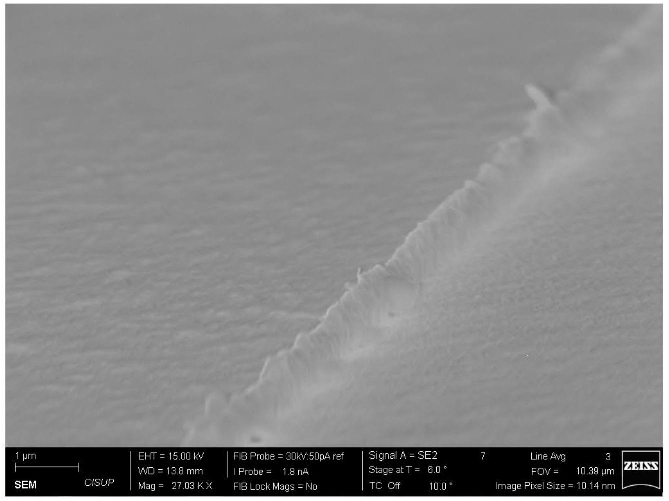

5 µm
SEM
CISUP
EHT = 15.00 kV
WD = 10.0 mm
Mag = 4.81 K X
FIB Probe = 30kV:50pA ref
I Probe = 1.2 nA
FIB Lock Mags = No
Signal A = SE2
Stage at T = 0.0 °
TC Off 54.0 °
7
Line Avg 3
FOV = 58.32 µm
Image Pixel Size = 56.96 nm
ZEISS

Grating coupler: Receiver
The small square on the left was used for calibrate FIB etching using an atomic force microscope

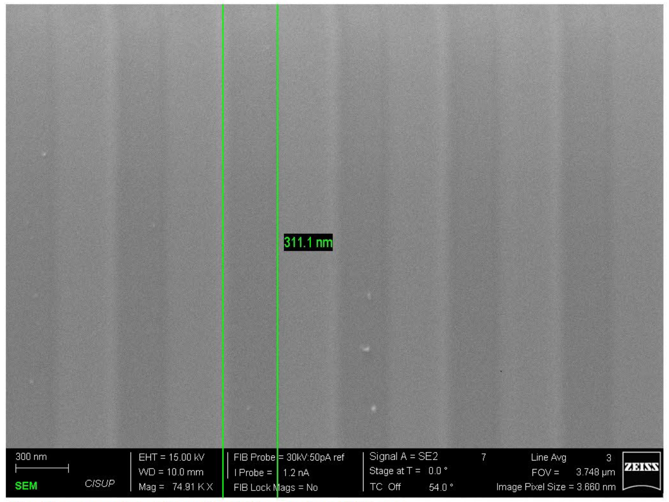

5 µm
SEM
CISUP
EHT = 15.00 kV
WD = 10.0 mm
Mag = 4.81 K X
FIB Probe = 30kV:50pA ref
I Probe = 1.2 nA
FIB Lock Mags = No
Signal A = SE2
Stage at T = 0.0 °
TC Off 54.0 °
7
Line Avg 3
FOV = 58.32 µm
Image Pixel Size = 56.96 nm
ZEISS

Grating coupler: Emitter


3 µm
SEM
CISUP
EHT = 15.00 kV
WD = 11.4 mm
Mag = 7.50 K X
FIB Probe = 30kV:50pA ref
I Probe = 1.3 nA
FIB Lock Mags = No
Signal A = SE2
Stage at T = 0.0 °
TC Off 33.7 °
7
Line Avg 3
FOV = 37.44 µm
Image Pixel Size = 36.57 nm
ZEISS


1 µm
SEM
CISUP
EHT = 15.00 kV
WD = 13.8 mm
Mag = 27.03 K X
FIB Probe = 30kV:50pA ref
I Probe = 1.8 nA
FIB Lock Mags = No
Signal A = SE2
Stage at T = 6.0 °
TC Off 10.0 °
7
Line Avg 3
FOV = 10.39 µm
Image Pixel Size = 10.14 nm
ZEISS

Vertical R.I.E etching with CF4

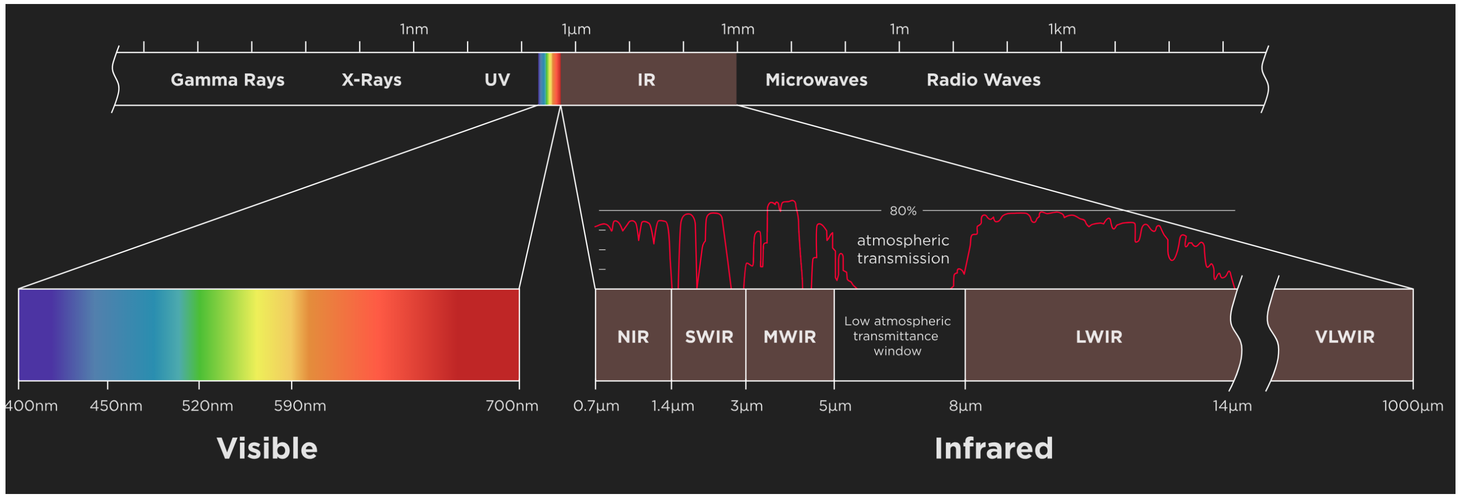

311.1 nm
300 nm
SEM
CISUP
EHT = 15.00 kV
WD = 10.0 mm
Mag = 74.91 K X
FIB Probe = 30kV:50pA ref
I Probe = 1.2 nA
FIB Lock Mags = No
Signal A = SE2
Stage at T = 0.0 °
TC Off 54.0 °
7
Line Avg 3
FOV = 3.748 µm
Image Pixel Size = 3.660 nm
ZEISS

Grating coupler: Expected dimension 315 nm

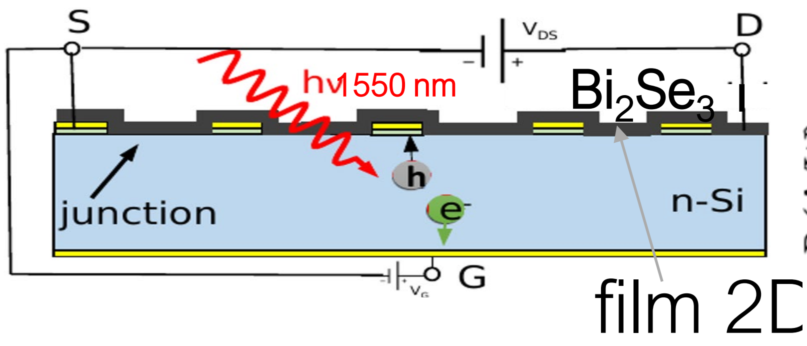
- Prodotte principalmente @DII ma in parte @ INFN-PI
- Abbiamo acquisito il know-how per produrre in house strutture SoI in Si + metallizzazioni
- PE-CVD per deposito di SiO2 …

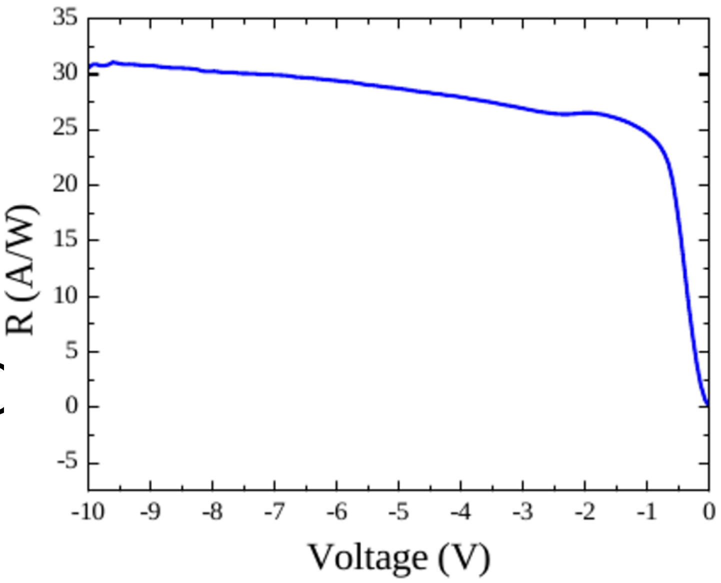
QUANTEP: sviluppo di rivelatori IR di singolo fotone

- Dispositivi commerciali in banda SWIR (1550 nm)
- Single photon: superconduttori, criogenici, poco efficienti
- Non single-photon: fotodiodi basati su InGaAs (0.9 – 1.7 um), raffreddati responsività tipica 1Amp/Watt

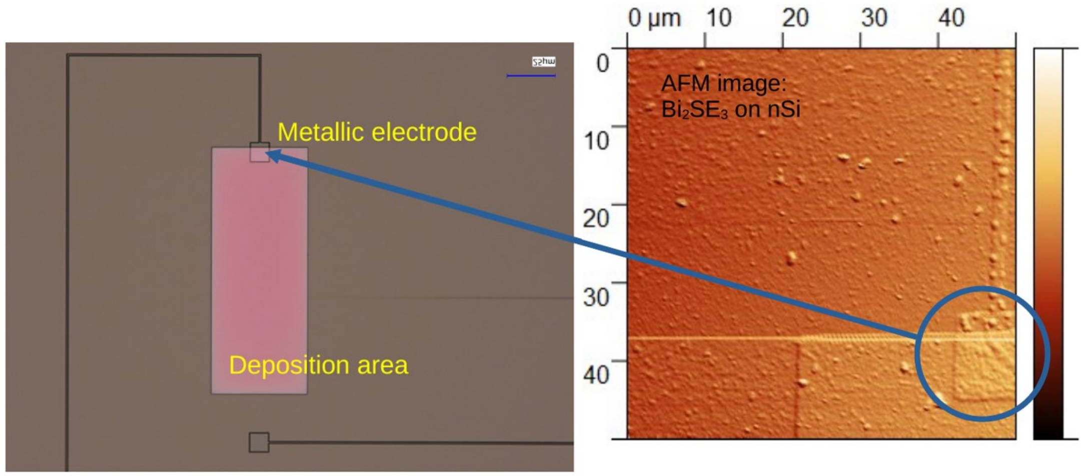

1nm
1µm
1mm
1m
1km
Gamma Rays
X-Rays
UV
IR
Microwaves
Radio Waves
80%
atmospheric transmission
NIR
SWIR
MWIR
Low atmospheric transmittance window
LWIR
VLWIR
400nm
450nm
520nm
590nm
700nm
0.7µm
1.4µm
3µm
5µm
8µm
14µm
1000µm
Visible
Infrared

- Fondamentali per implementazione di algoritmi di QC fotonici
- QUANTEP: sviluppo di rivelatori basati su etero-giunzioni Bi_2Se_3/Si (bandGap = 0.32 eV)


S
D
V_{DS}
hν1550 nm
Bi_2Se_3
junction
h
e⁻
n-Si
V_G
G
film 2D



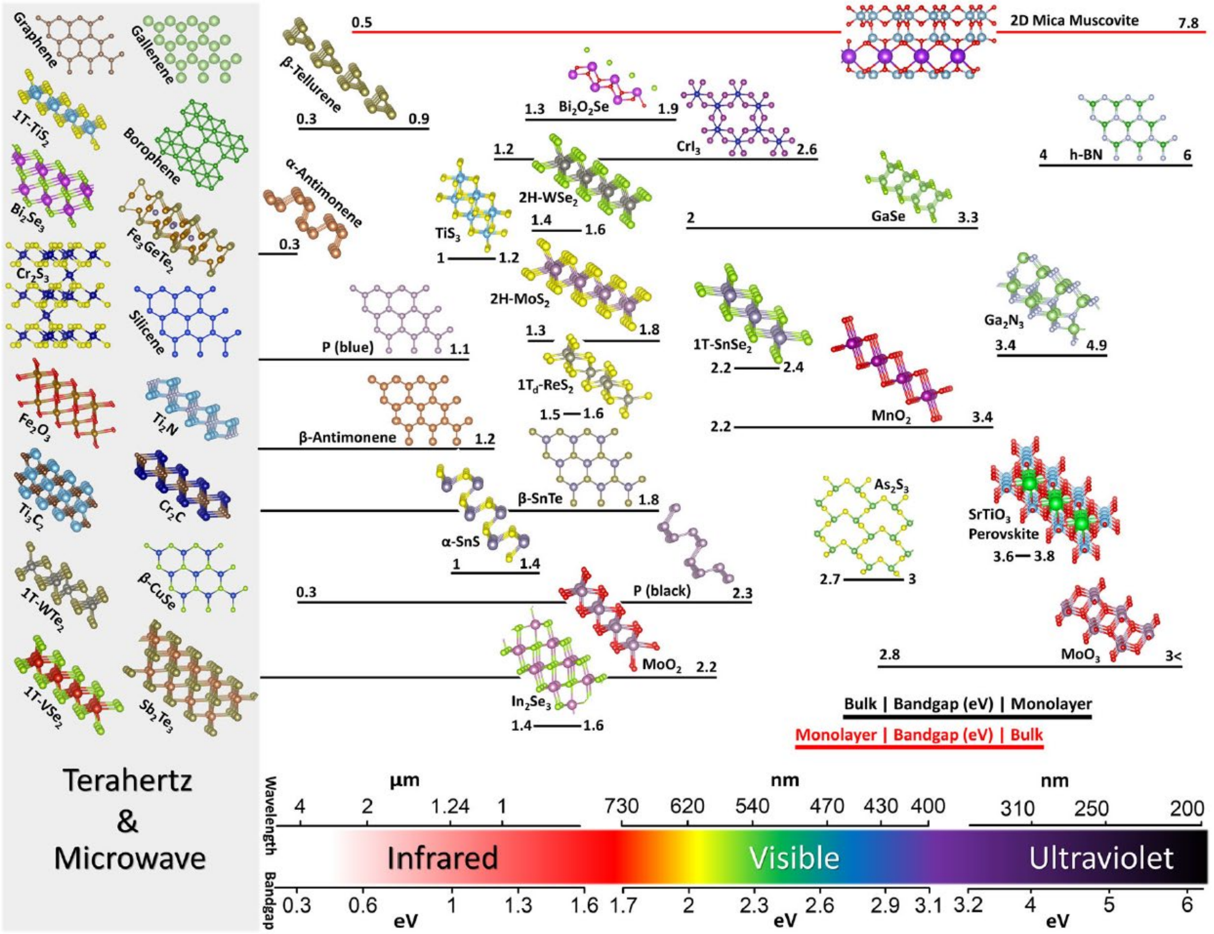
R = 30 Amp/W @ -10V bias

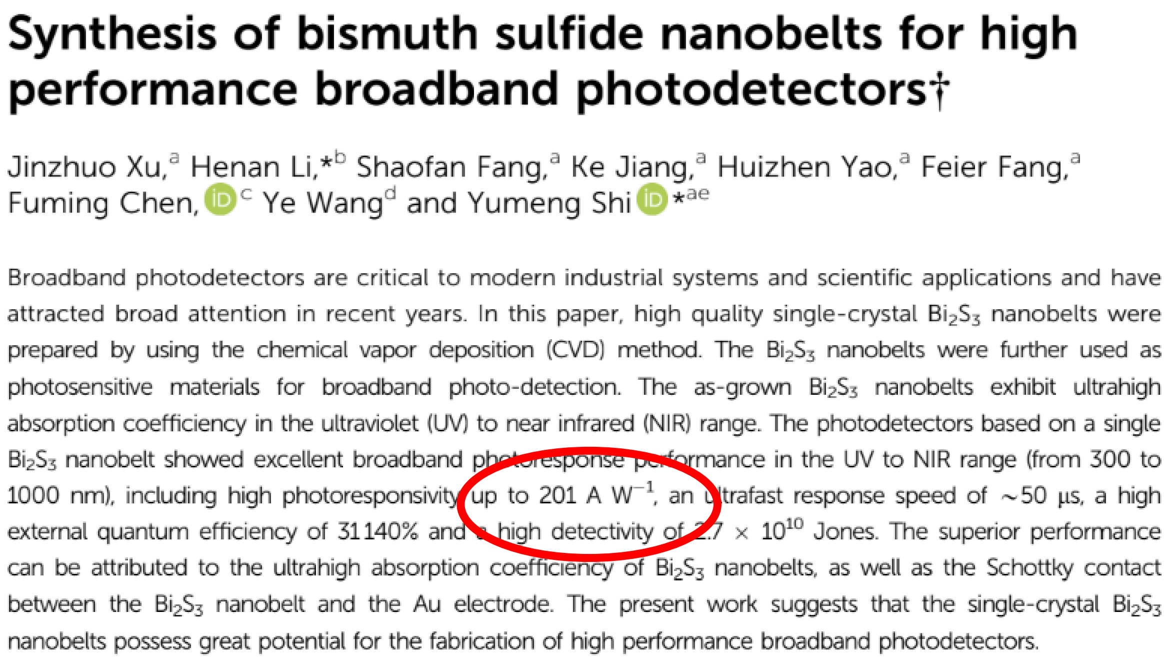

Metallic electrode
Deposition area
0 µm
10
20
30
40
AFM image:
Bi_2SE_3 on nSi

@ RM2

Nuova proposta NANO-SWIR

- Sviluppo di sensori IR ad altissima sensibilità e larga banda SWIR (1 – 3 um) – MWIR (3 - 8 um)
- Utilizzo di materiali innovativi basati su materiali topologici o di Van Der Waals (articoli 2022 …)
- Deposito tramite 2D: OK ma la struttura cristallina limita la responsività R
    - R aumenta moltissimo se in forma 1D : nanowires/nanobelts/flakes


Graphene
Gallenene
1T-TiS$_2$
Borophene
Bi$_2$Se$_3$
Fe$_3$GeTe$_2$
Cr$_2$S$_3$
Silicene
Fe$_2$O$_3$
Ti$_2$N
Ti$_3$C$_2$
Cr$_2$C
1T-WTe$_2$
β-CuSe
1T-VSe$_2$
Sb$_2$Te$_3$
Terahertz & Microwave
0.5
2D Mica Muscovite
7.8
β-Tellurene
0.3
0.9
1.3
Bi$_2$O$_2$Se
1.9
CrI$_3$
1.2
2.6
h-BN
4
6
α-Antimonene
0.3
TiS$_3$
1
1.2
2H-WSe$_2$
1.4
1.6
2
GaSe
3.3
2H-MoS$_2$
1.3
1.8
1T-SnSe$_2$
2.2
2.4
Ga$_2$N$_3$
3.4
4.9
P (blue)
1.1
1T$_d$-ReS$_2$
1.5
1.6
MnO$_2$
2.2
3.4
β-Antimonene
1.2
β-SnTe
1.8
α-SnS
1
1.4
As$_2$S$_3$
2.7
3
SrTiO$_3$ Perovskite
3.6
3.8
0.3
P (black)
2.3
MoO$_2$
2.2
MoO$_3$
2.8
3<
In$_2$Se$_3$
1.4
1.6
Bulk | Bandgap (eV) | Monolayer
Monolayer | Bandgap (eV) | Bulk
Wavelength
µm
4
2
1.24
1
nm
730
620
540
470
430
400
nm
310
250
200
Infrared
Visible
Ultraviolet
Bandgap
0.3
0.6
1
1.3
1.6
1.7
2
2.3
2.6
2.9
3.1
3.2
4
5
6
eV
eV
eV

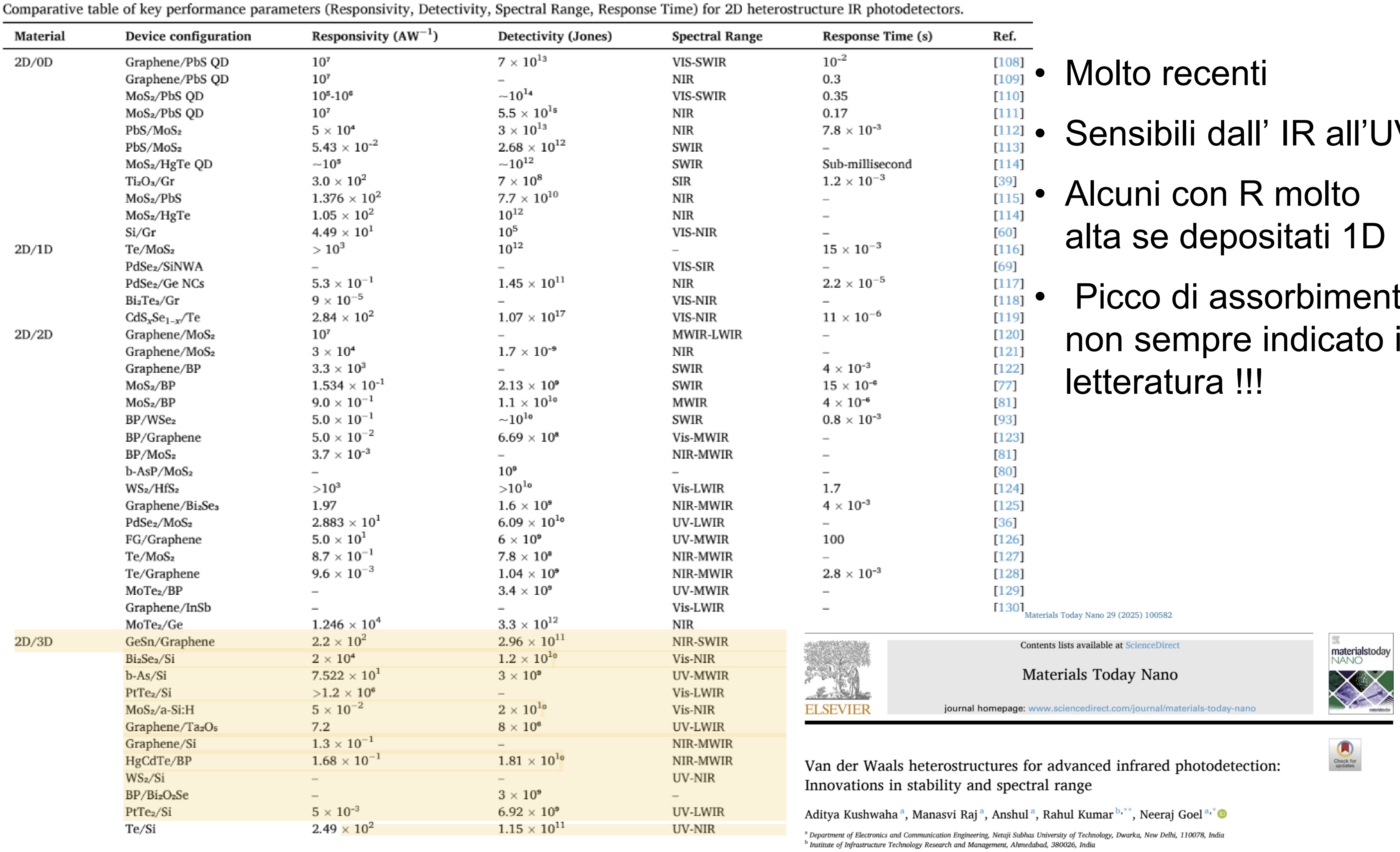


Synthesis of bismuth sulfide nanobelts for high performance broadband photodetectors†

Jinzhuo Xu,[a] Henan Li,*[b] Shaofan Fang,[a] Ke Jiang,[a] Huizhen Yao,[a] Feier Fang,[a] Fuming Chen,[c] Ye Wang[d] and Yumeng Shi *[ae]

Broadband photodetectors are critical to modern industrial systems and scientific applications and have attracted broad attention in recent years. In this paper, high quality single-crystal Bi_2S_3 nanobelts were prepared by using the chemical vapor deposition (CVD) method. The Bi_2S_3 nanobelts were further used as photosensitive materials for broadband photo-detection. The as-grown Bi_2S_3 nanobelts exhibit ultrahigh absorption coefficiency in the ultraviolet (UV) to near infrared (NIR) range. The photodetectors based on a single Bi_2S_3 nanobelt showed excellent broadband photoresponse performance in the UV to NIR range (from 300 to 1000 nm), including high photoresponsivity up to 201 A W^{-1}, an ultrafast response speed of ~50 μs, a high external quantum efficiency of 31140% and a high detectivity of 2.7 × 10^{10} Jones. The superior performance can be attributed to the ultrahigh absorption coefficiency of Bi_2S_3 nanobelts, as well as the Schottky contact between the Bi_2S_3 nanobelt and the Au electrode. The present work suggests that the single-crystal Bi_2S_3 nanobelts possess great potential for the fabrication of high performance broadband photodetectors.

Materiali 1D/2D, Pavia, Pisa Roma 2



Comparative table of key performance parameters (Responsivity, Detectivity, Spectral Range, Response Time) for 2D heterostructure IR photodetectors.

Material	Device configuration	Responsivity (AW^{-1})	Detectivity (Jones)	Spectral Range	Response Time (s)	Ref.
2D/0D	Graphene/PbS QD	10^7	7×10^{13}	VIS-SWIR	10^{-2}	[108]
	Graphene/PbS QD	10^7	–	NIR	0.3	[109]
	MoS$_2$/PbS QD	10^5-10^6	$\sim 10^{14}$	VIS-SWIR	0.35	[110]
	MoS$_2$/PbS QD	10^7	5.5×10^{15}	NIR	0.17	[111]
	PbS/MoS$_2$	5×10^4	3×10^{13}	NIR	7.8×10^{-3}	[112]
	PbS/MoS$_2$	5.43×10^{-2}	2.68×10^{12}	SWIR	–	[113]
	MoS$_2$/HgTe QD	$\sim 10^5$	$\sim 10^{12}$	SWIR	Sub-millisecond	[114]
	Ti$_2$O$_3$/Gr	3.0×10^2	7×10^8	SIR	1.2×10^{-3}	[39]
	MoS$_2$/PbS	1.376×10^2	7.7×10^{10}	NIR	–	[115]
	MoS$_2$/HgTe	1.05×10^2	10^{12}	NIR	–	[114]
	Si/Gr	4.49×10^1	10^5	VIS-NIR	–	[60]
2D/1D	Te/MoS$_2$	$> 10^3$	10^{12}	–	15×10^{-3}	[116]
	PdSe$_2$/SiNWA	–	–	VIS-SIR	–	[69]
	PdSe$_2$/Ge NCs	5.3×10^{-1}	1.45×10^{11}	NIR	2.2×10^{-5}	[117]
	Bi$_2$Te$_3$/Gr	9×10^{-5}	–	VIS-NIR	–	[118]
	CdS$_x$Se$_{1-x}$/Te	2.84×10^2	1.07×10^{17}	VIS-NIR	11×10^{-6}	[119]
2D/2D	Graphene/MoS$_2$	10^7	–	MWIR-LWIR	–	[120]
	Graphene/MoS$_2$	3×10^4	1.7×10^{-9}	NIR	–	[121]
	Graphene/BP	3.3×10^3	–	SWIR	4×10^{-3}	[122]
	MoS$_2$/BP	1.534×10^{-1}	2.13×10^9	SWIR	15×10^{-6}	[77]
	MoS$_2$/BP	9.0×10^{-1}	1.1×10^{10}	MWIR	4×10^{-6}	[81]
	BP/WSe$_2$	5.0×10^{-1}	$\sim 10^{10}$	SWIR	0.8×10^{-3}	[93]
	BP/Graphene	5.0×10^{-2}	6.69×10^8	Vis-MWIR	–	[123]
	BP/MoS$_2$	3.7×10^{-3}	–	NIR-MWIR	–	[81]
	b-AsP/MoS$_2$	–	10^9	–	–	[80]
	WS$_2$/HfS$_2$	$>10^3$	$>10^{10}$	Vis-LWIR	1.7	[124]
	Graphene/Bi$_2$Se$_3$	1.97	1.6×10^9	NIR-MWIR	4×10^{-3}	[125]
	PdSe$_2$/MoS$_2$	2.883×10^1	6.09×10^{10}	UV-LWIR	–	[36]
	FG/Graphene	5.0×10^1	6×10^9	UV-MWIR	100	[126]
	Te/MoS$_2$	8.7×10^{-1}	7.8×10^8	NIR-MWIR	–	[127]
	Te/Graphene	9.6×10^{-3}	1.04×10^9	NIR-MWIR	2.8×10^{-3}	[128]
	MoTe$_2$/BP	–	3.4×10^9	UV-MWIR	–	[129]
	Graphene/InSb	–	–	Vis-LWIR	–	[130]
	MoTe$_2$/Ge	1.246×10^4	3.3×10^{12}	NIR		
2D/3D	GeSn/Graphene	2.2×10^2	2.96×10^{11}	NIR-SWIR		
	Bi$_2$Se$_3$/Si	2×10^4	1.2×10^{10}	Vis-NIR		
	b-As/Si	7.522×10^1	3×10^9	UV-MWIR		
	PtTe$_2$/Si	$>1.2 \times 10^6$	–	Vis-LWIR		
	MoS$_2$/a-Si:H	5×10^{-2}	2×10^{10}	Vis-NIR		
	Graphene/Ta$_2$O$_5$	7.2	8×10^6	UV-LWIR		
	Graphene/Si	1.3×10^{-1}	–	NIR-MWIR		
	HgCdTe/BP	1.68×10^{-1}	1.81×10^{10}	NIR-MWIR		
	WS$_2$/Si	–	–	UV-NIR		
	BP/Bi$_2$O$_2$Se	–	3×10^9	–		
	PtTe$_2$/Si	5×10^{-3}	6.92×10^9	UV-LWIR		
	Te/Si	2.49×10^2	1.15×10^{11}	UV-NIR		

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Van der Waals heterostructures for advanced infrared photodetection: Innovations in stability and spectral range

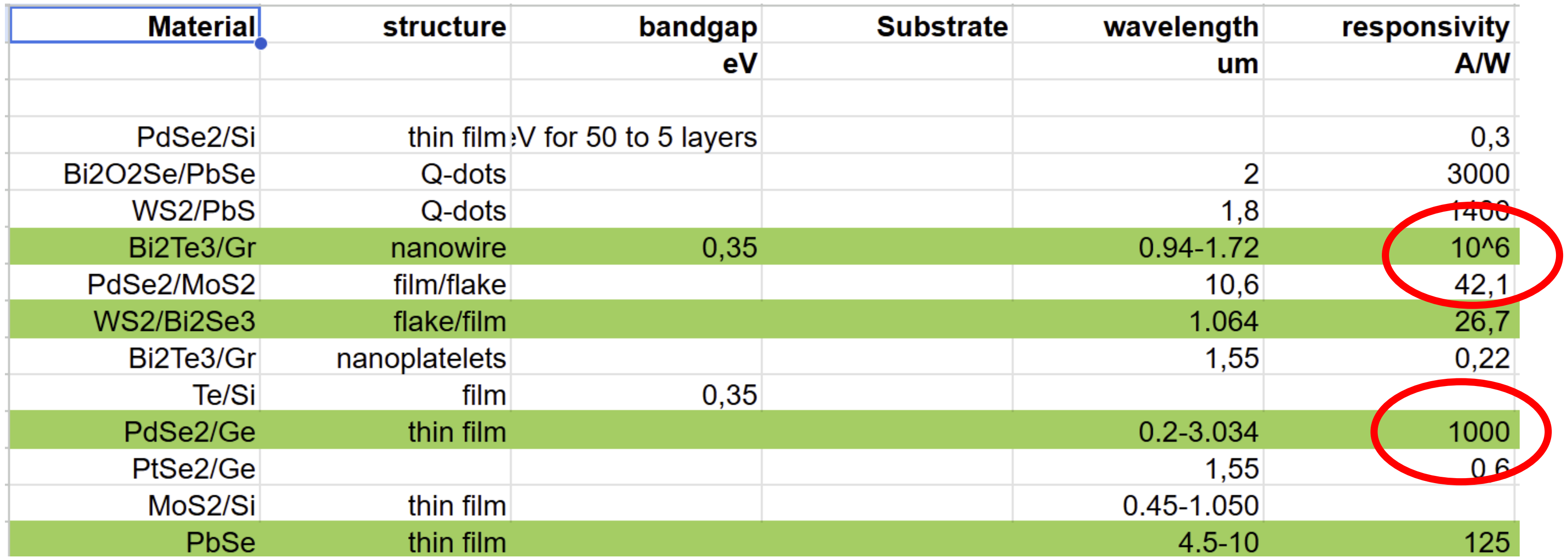
Aditya Kushwaha [a], Manasvi Raj [a], Anshul [a], Rahul Kumar [b,**], Neeraj Goel [a,*]

[a] Department of Electronics and Communication Engineering, Netaji Subhas University of Technology, Dwarka, New Delhi, 110078, India
[b] Institute of Infrastructure Technology Research and Management, Ahmedabad, 380026, India

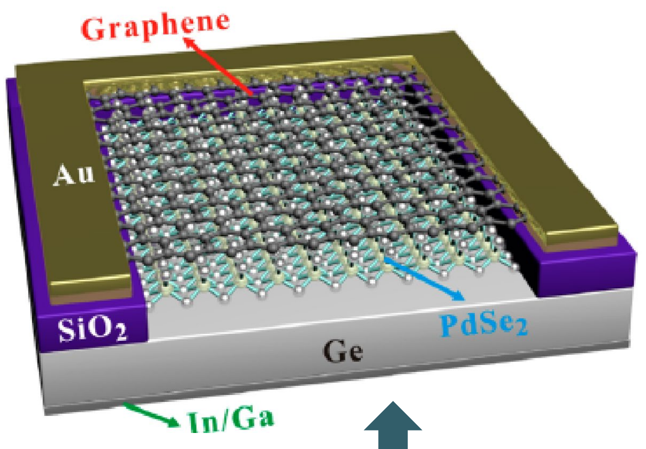
- Molto recenti
- Sensibili dall' IR all'UV
- Alcuni con R molto alta se depositati 1D
- Picco di assorbimento non sempre indicato in letteratura !!!

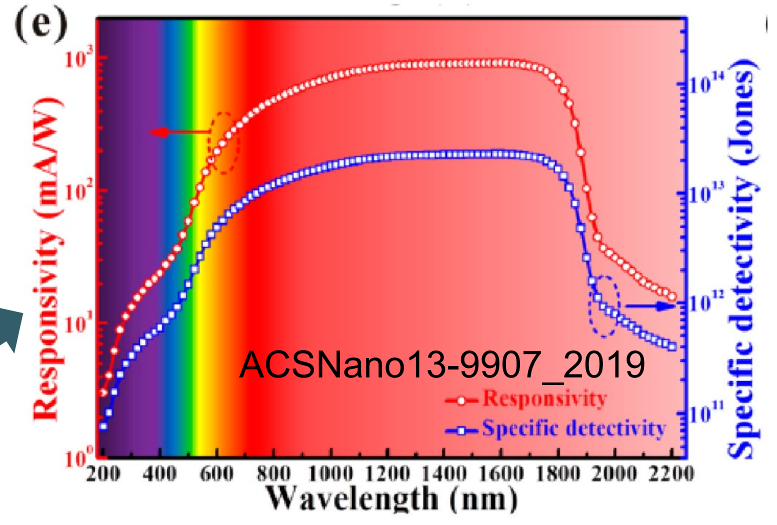
Cosa si propone il progetto ?
Fase 1: caratterizzazione dei materiali, Pavia

- Caratterizzare la risposta spettrale di diversi materiali
- Sceglierne 4 che coprono la banda 1-8 um con la massima responsivita' e separazione spettrale

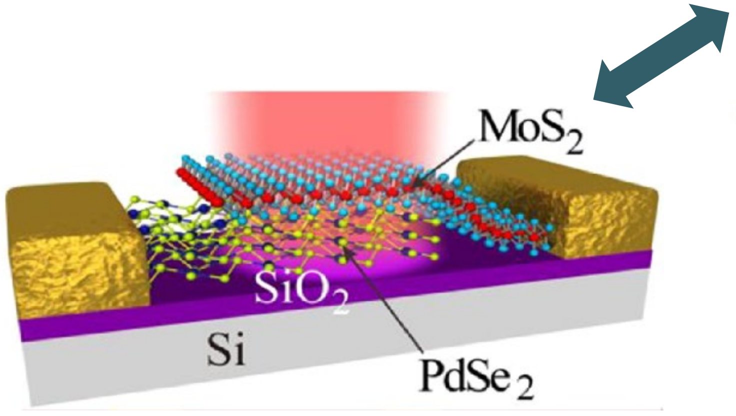


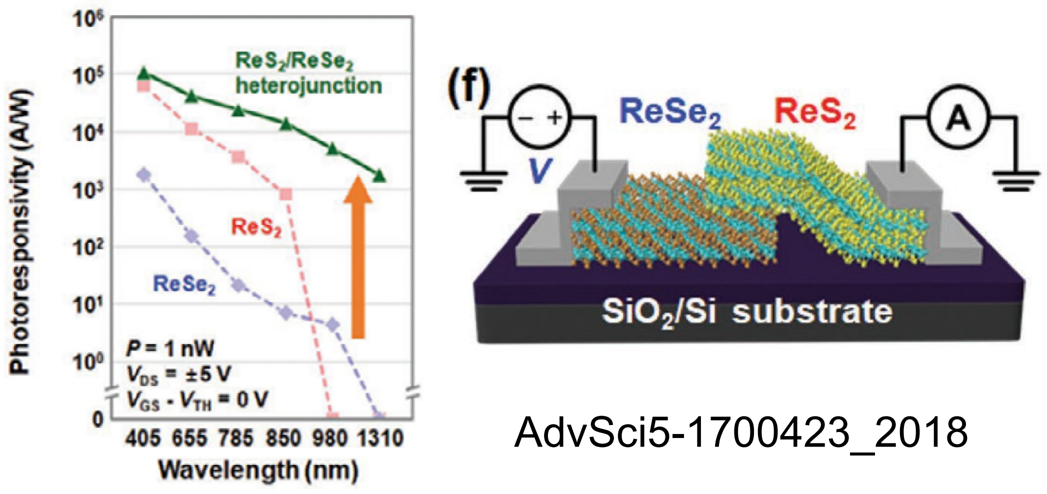
Material	structure	bandgap eV	Substrate	wavelength um	responsivity A/W
PdSe2/Si	thin film	:V for 50 to 5 layers			0,3
Bi2O2Se/PbSe	Q-dots			2	3000
WS2/PbS	Q-dots			1,8	1400
Bi2Te3/Gr	nanowire	0,35		0.94-1.72	10^6
PdSe2/MoS2	film/flake			10,6	42,1
WS2/Bi2Se3	flake/film			1.064	26,7
Bi2Te3/Gr	nanoplatelets			1,55	0,22
Te/Si	film	0,35			
PdSe2/Ge	thin film			0.2-3.034	1000
PtSe2/Ge				1,55	0,6
MoS2/Si	thin film			0.45-1.050	
PbSe	thin film			4.5-10	125





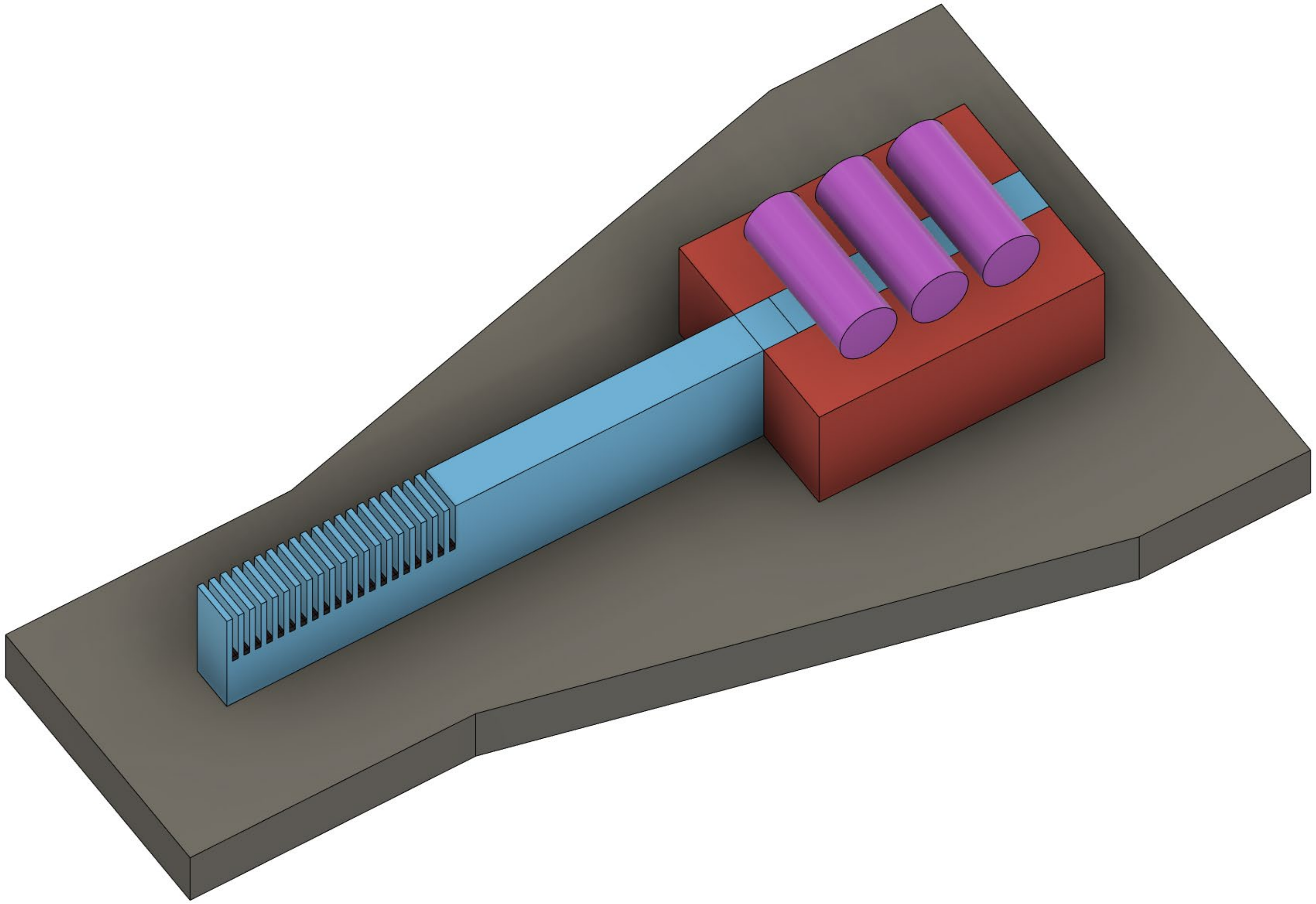
ACSNano13-9907_2019





AdvSci5-1700423_2018

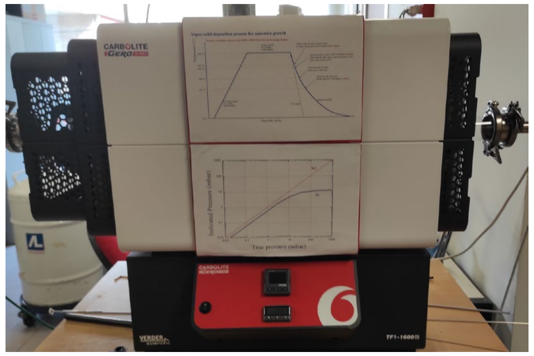
Prototipo 1 pixel – 1 materiale, Pisa



- Prototipo rivelatore 1 pixel in silicon photonics
- Deposito nanowire/nanobelts/flakes a seconda del materiale
- Test

Sequenza delle operazioni, Pavia, Pisa, Roma2

1) sintesi delle strutture 2D & 1D su quarzo @RM2

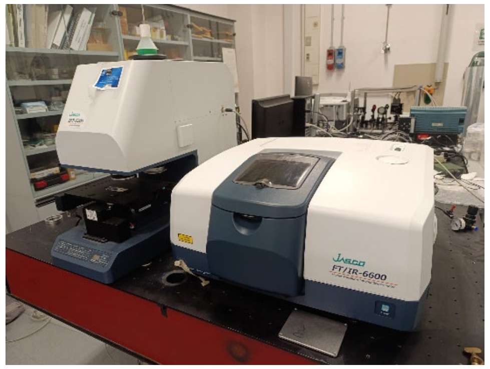


Forno zona singola

Forno 3 zone

2) misura spettro 2D @ PI (DF) , RM2

Spettrometro 3um



Lab ottica @ DF

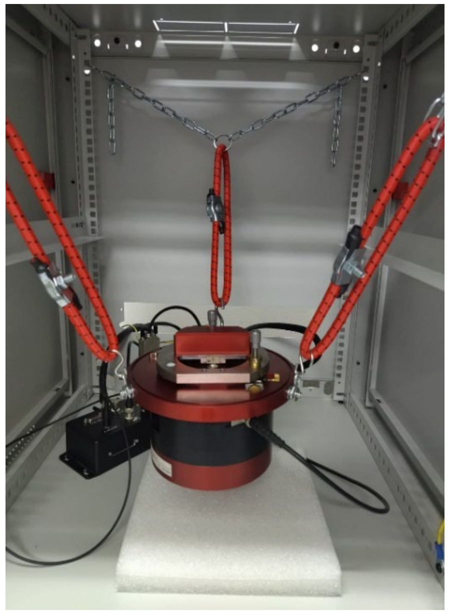
3) produzione struttura in silicon photonics @ PI

4) posizionamento nanowire (1D) @ PV (UNIMORE)

Nano manipolatore

5) test del sensore (curva I-V, R(λ)) @PI,RM2,PV

Micro manipolatore



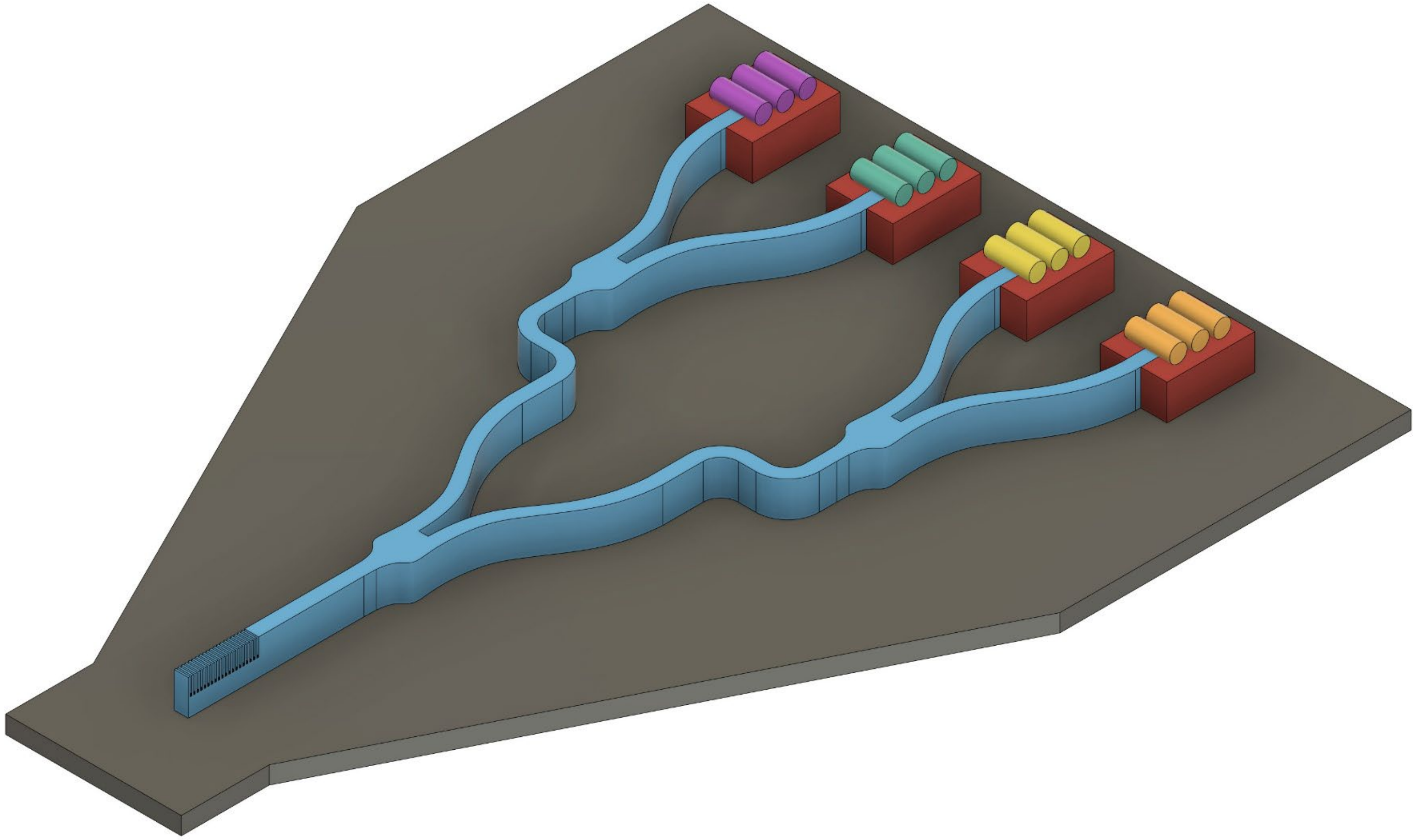
AFM

Laser IR 1.4-1.7 um

Source + pA

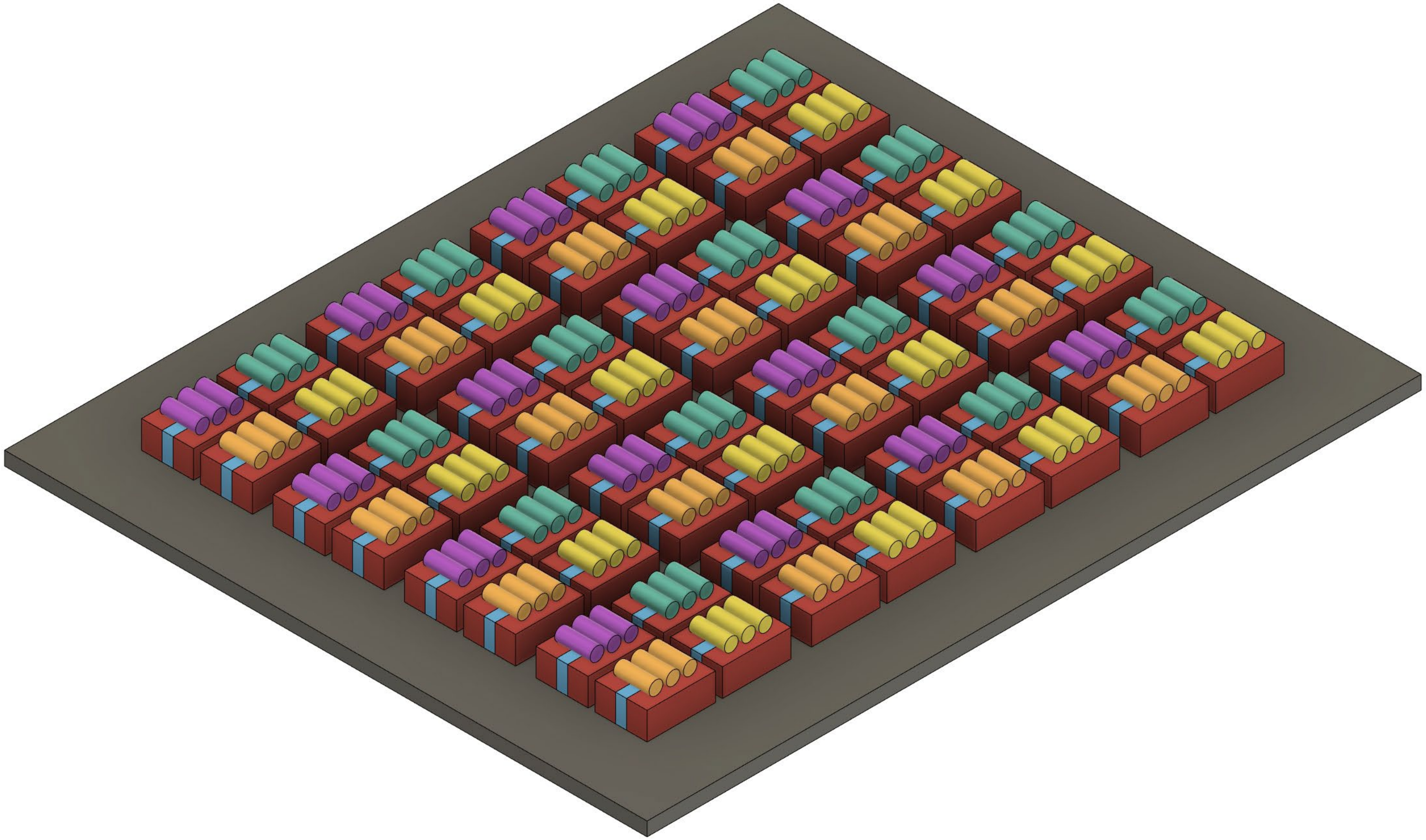
Cosa si propone il progetto ?
Fase 2: struttura 4 materiali + guida Si

- Sviluppo di un sensore a larga banda 1-8 um basato su nanostrutture 1D di 4 materiali diversi con diversa risposta spettrale, ingresso in fibra e struttura in silicon photonics



- Risposte indipendenti: analisi spettrale a bassa risoluzione
- Alta sensibilita' su tutta la banda (goal : 10x InGaAs)
- Il Si non trasmette nel visibile : intrinsicamente solar blind
- Dimensioni ridotte: semplice da raffreddare per diminuire il rumore termico (MWIR)

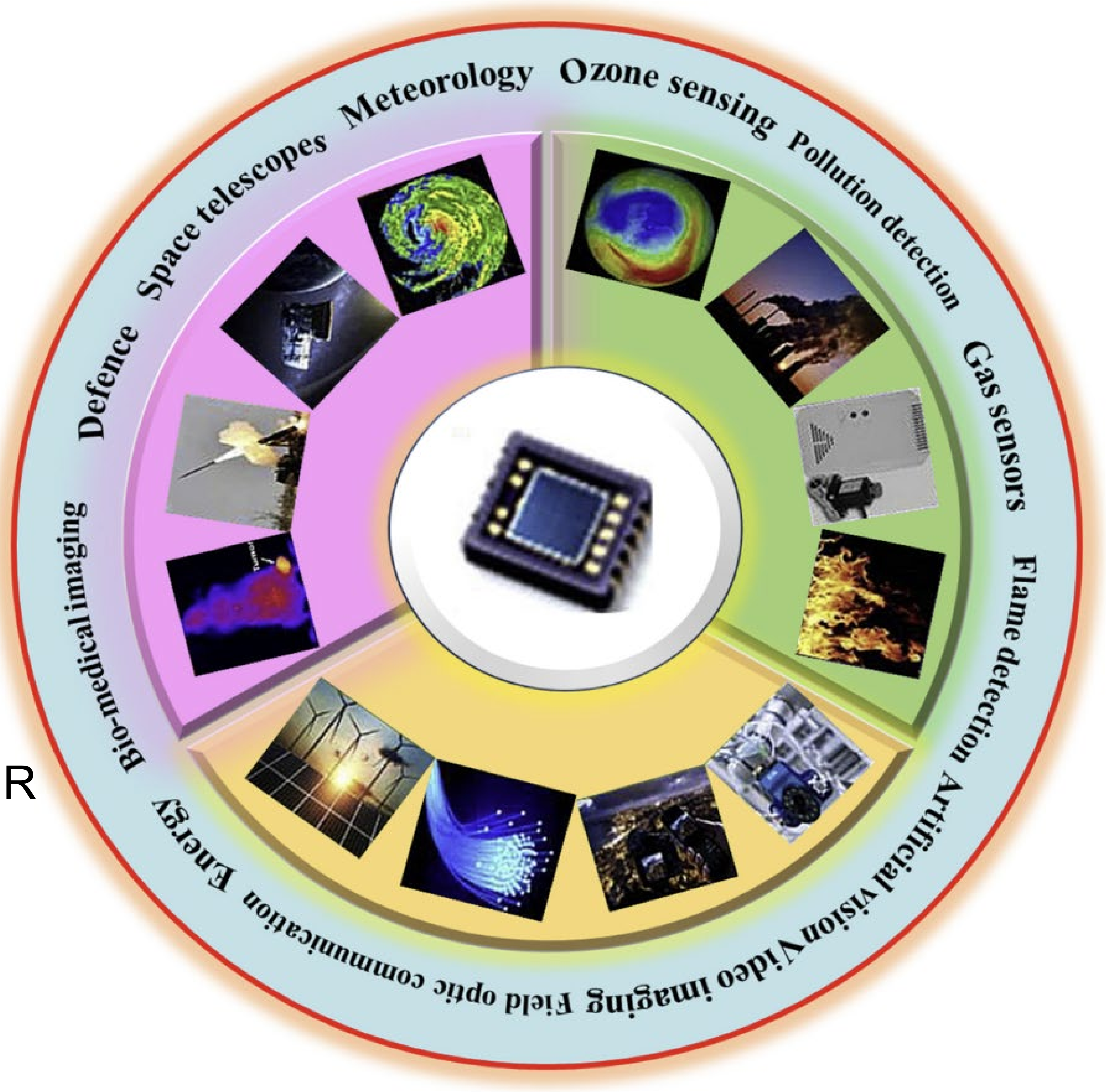
Cosa si propone il progetto ?
Fase 3: Struttura 64 pixel-16 gruppi-4 materiali



- Dimostratore: Array 8 * 8 (4*4 gruppi), lettura singolo pixel, polarizzazione a gruppi di 16
  - posizionamento molti nanowires complesso
- Accoppiamento luce dall’alto (filtro passa basso commerciale) o dal basso usando il Si come filtro per il visibile
- Altre combinazioni possibili es. sensore 8*8 singolo materiale su banda ristretta

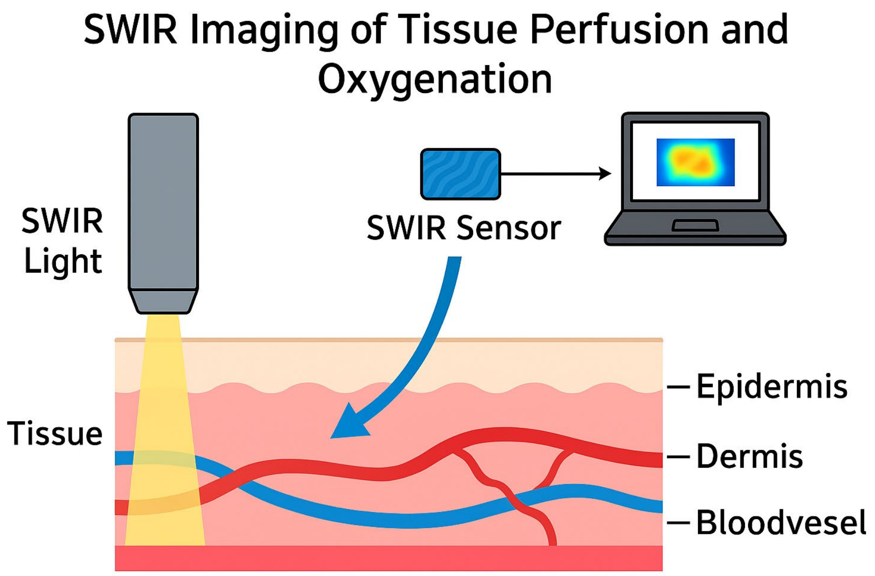
Applicazioni sensori SWIR ad altissima sensibilità

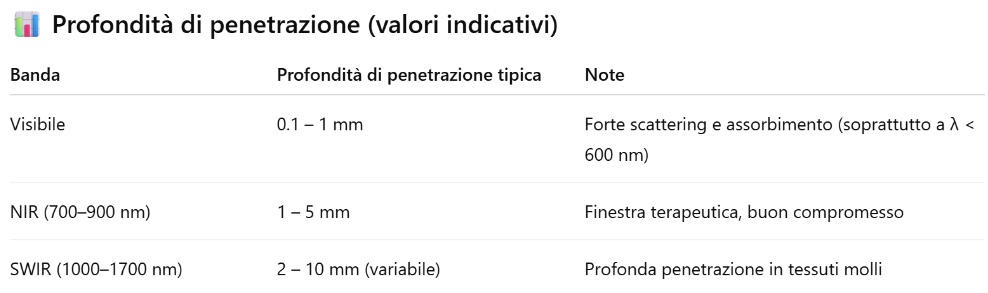
- Possibili utilizzi in molti campi, limitati attualmente dall’ alto costo, moderata sensibilità e larghezza di banda (1-1.7 um)
  dei dispositivi commerciali InGaAs
- Pochissimi array commerciali in banda SWIR – MWIR
- Campi di utilizzo:
  - Scienze della vita
  - Agricoltura di precisione
  - Fisica dell’atmosfera, astronomia IR
  - Analisi molecolare
  - Homeland security


Bio-medical imaging
Defence
Space telescopes
Meteorology
Ozone sensing
Pollution detection
Gas sensors
Flame detection
Artificial vision
Video imaging
Field optic communication
Energy

Monitoraggio non invasivo della perfusione

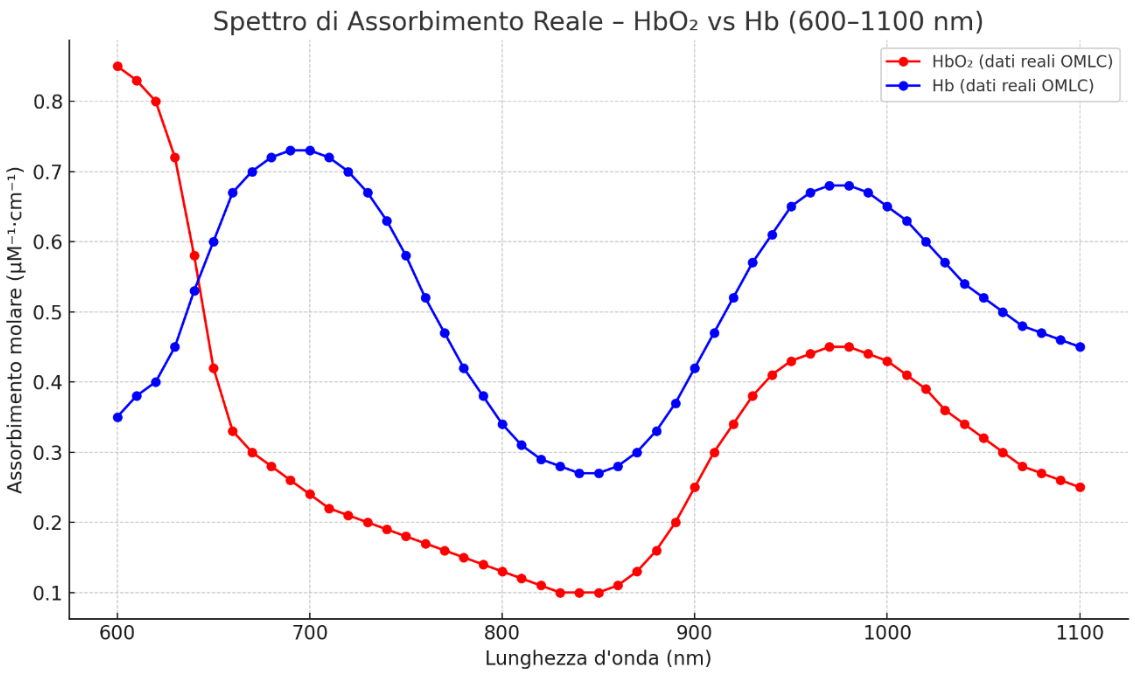
- Monitoraggio non invasivo della perfusione e dell’ossigenazione tissutale
  - Limiti delle tecniche attuali (pulsossimetria, doppler, imaging termico) in termini di profondità di analisi e accuratezza
  - SWIR (1 -3 um) penetrano molto di più del visibile nei tessuti
    - Differenziazione spettrale delle forme di emoglobina nell IR -> mappe spaziali delle condizioni circolatorie locali (array SWIR)


SWIR Imaging of Tissue Perfusion and Oxygenation
SWIR Light
SWIR Sensor
Tissue
Epidermis
Dermis
Bloodvesel



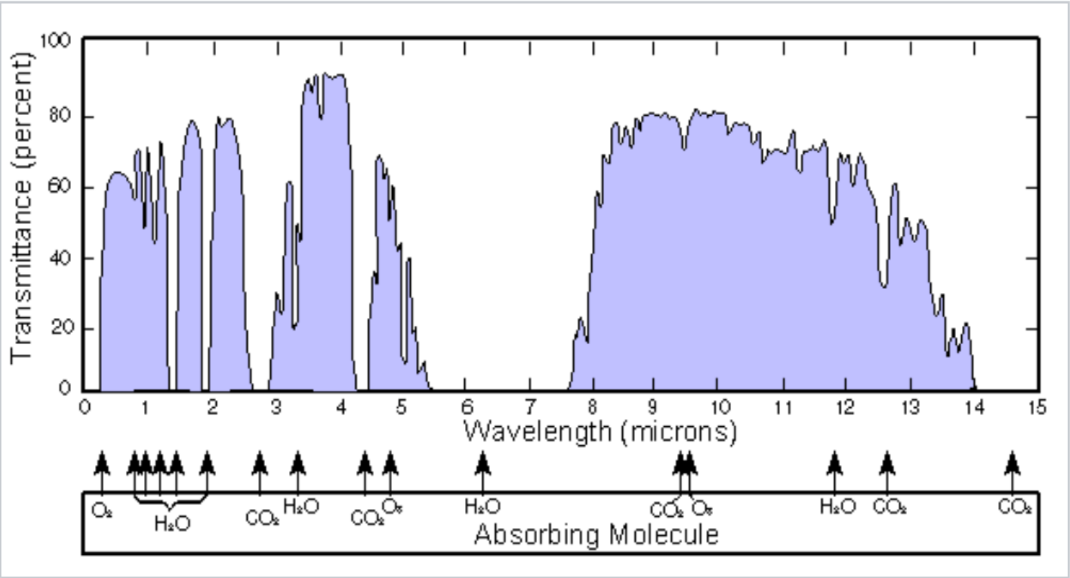
📊 Profondità di penetrazione (valori indicativi)

Banda	Profondità di penetrazione tipica	Note
Visibile	0.1 – 1 mm	Forte scattering e assorbimento (soprattutto a λ < 600 nm)
NIR (700–900 nm)	1 – 5 mm	Finestra terapeutica, buon compromesso
SWIR (1000–1700 nm)	2 – 10 mm (variabile)	Profonda penetrazione in tessuti molli

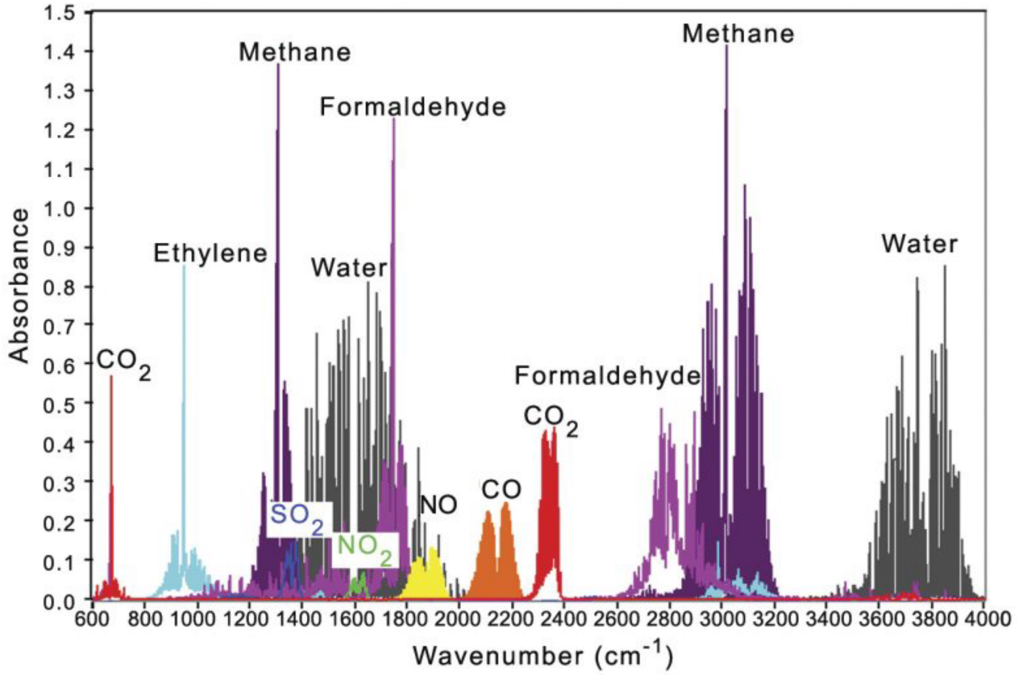


Pochi dati oltre 1.1 um

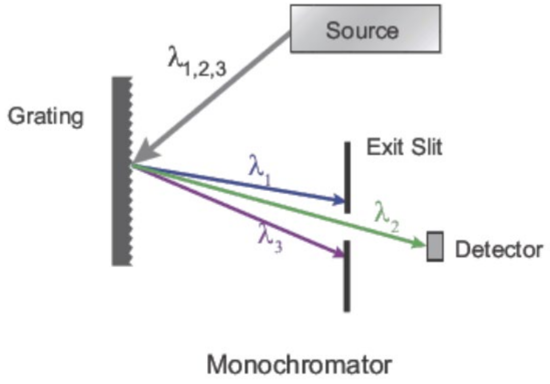
Sensori per astronomia IR – spettroscopia IR



- Astronomia IR: osservazioni da terra in banda J (1.1 – 1.4 um)
- Finestra di trasmissione atmosferica centrata su 1.25 um



- Molte molecole assorbono in banda 1-4 um
- Homeland security


Source
$\lambda_{1,2,3}$
Grating
Exit Slit
λ_1
λ_2
λ_3
Detector
Monochromator

Necessità di sensori SWIR ad alta sensibilità

Agricoltura di precisione

Misure IR/SWIR sono molto comuni in agricoltura di precisione:

- **Rilevamento dello Stress Idrico Precoce:** L'acqua assorbe fortemente nel SWIR. Variazioni minime nel contenuto idrico delle piante possono essere rilevate prima che lo stress sia visibile.
- **Analisi della Composizione Chimica:** I segnali SWIR sono influenzati dalla presenza di zuccheri, proteine, lipidi e altri composti organici nelle piante e nel suolo.
- **Identificazione di Malattie e Parassiti:** Le alterazioni nella struttura cellulare o nella composizione chimica dovute a patogeni possono essere individuate in fase iniziale.
- **Mappatura del Suolo Dettagliata:** Valutazione del contenuto di umidità, materia organica e minerali nel suolo.
- **Monitoraggio della Maturazione dei Frutti:** Analisi non distruttiva del grado di maturazione e del contenuto zuccherino.

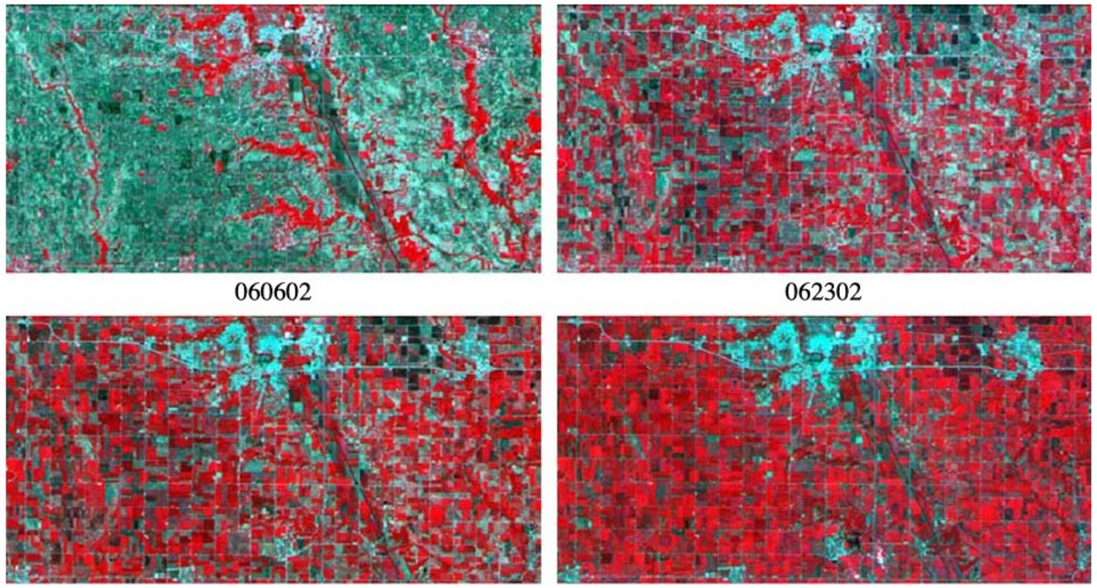
sensori SWIR ad alta sensibilità possono rilevare variazioni minime

Sensori SWIR spesso montati su droni o satelliti: necessità di array molto sensibili

$$\mathrm{VWC} = f\left(\frac{R_{NIR} - RSWIR}{R_{NIR} + RSWIR}\right)$$

Vegetation Water Content

array 8*8 2 materiali …



Jackson TJ, Chen D, Cosh M, Li F, Anderson M, Walthall C, Doriaswamy P, Hunt ER (2004) Vegetation water content mapping using Landsat data derived normalized difference water index for corn and soybeans. Remote Sens Environ 92:475–482

VWC Telsat VII image, Walnut AZ

- Anagrafica Pavia

- Bellani Vittorio	40%	UNIPV Resp. Loc.
- Boffelli Fabrizio	10%	INFN
- Restelli Simone	40%	UNIPV
- Rossella Francesco	20%	UNIPV

Richieste alla Sezione e budget

Budget annuale: 20 KEuro

Previsione spese 2026

- 4 Keuro: telecamera ad alta risoluzione per microscopi atomici.
- 7 Keuro: materiali e micro-probes per microscopia atomica e scanning tunneling
- 7 KEuro: materiali per processing di nano-materiali e nano-dispositivi
- 2 Keuro: Missioni presso i laboratori delle varie sezioni per lavori di micro-fabbricazione e micro-manipolazione.

Richieste alla Sezione:

- Servizio elettronica: montaggio nuova elettronica) + Laboratori-officina: montaggi strumenti; Totale: 0.5 mesi/anno.