3 iN innovative integrated instrumentation for nanoscience

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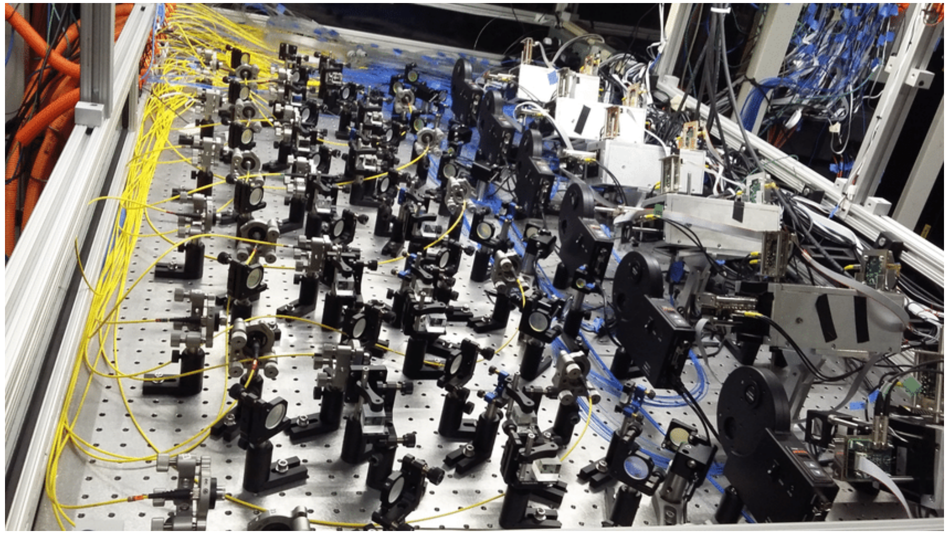
High Resolution Electronic Measurements in Nano-Bio Science

TRANSPARENT DETECTION OF LIGHT

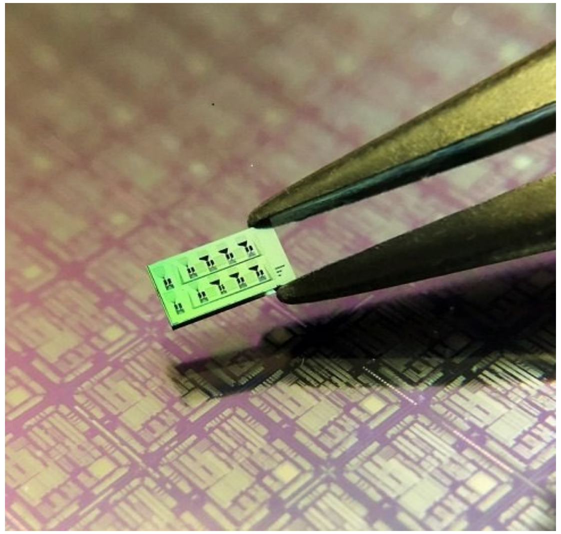
Francesco Zanetto

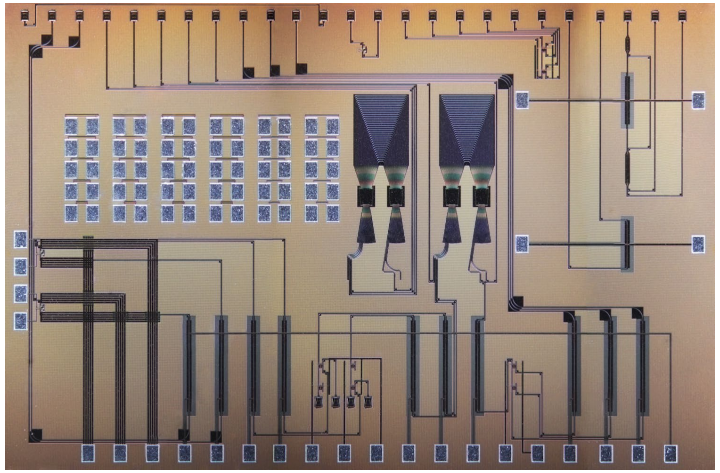
June 6th 2023

Traditional optics



Integrated photonics

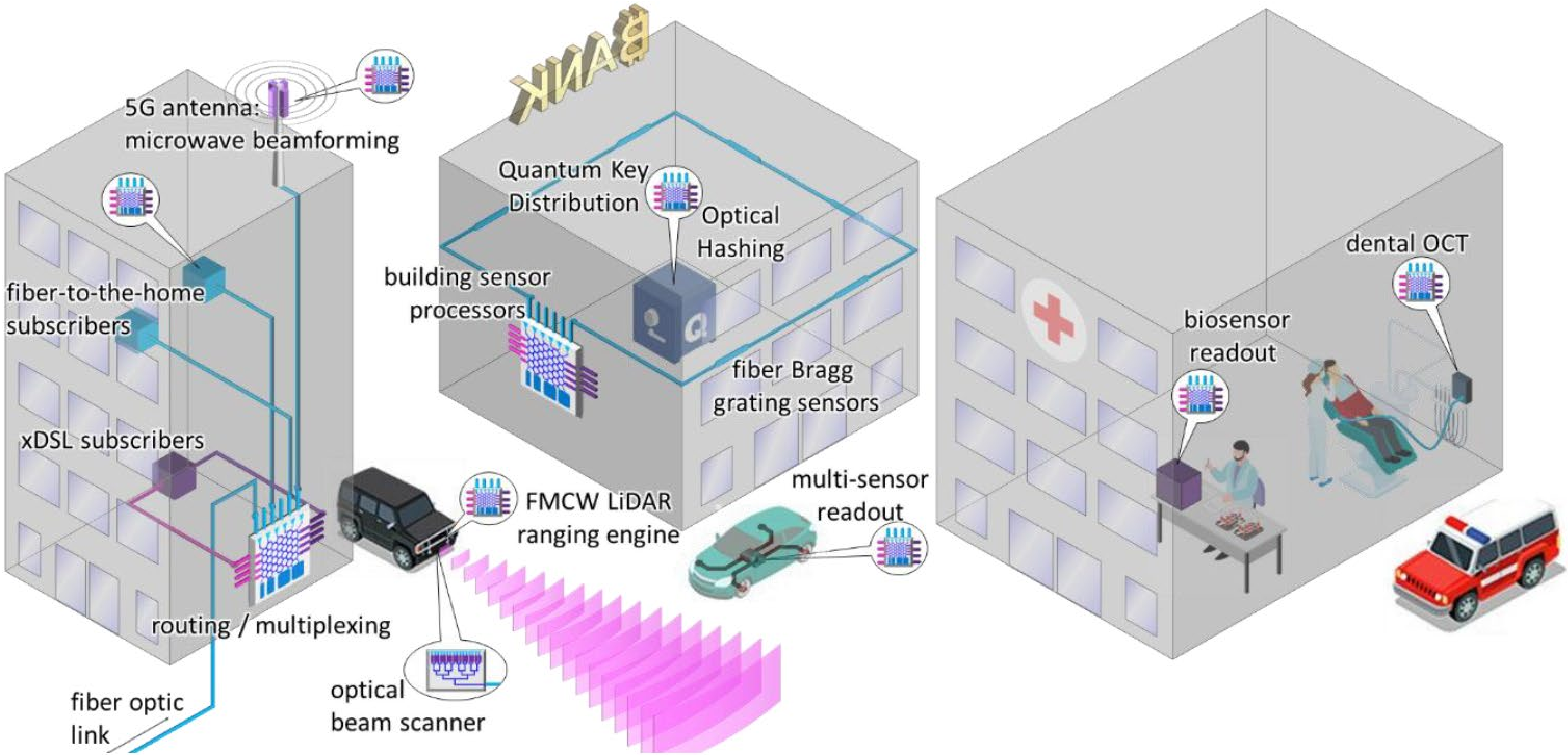




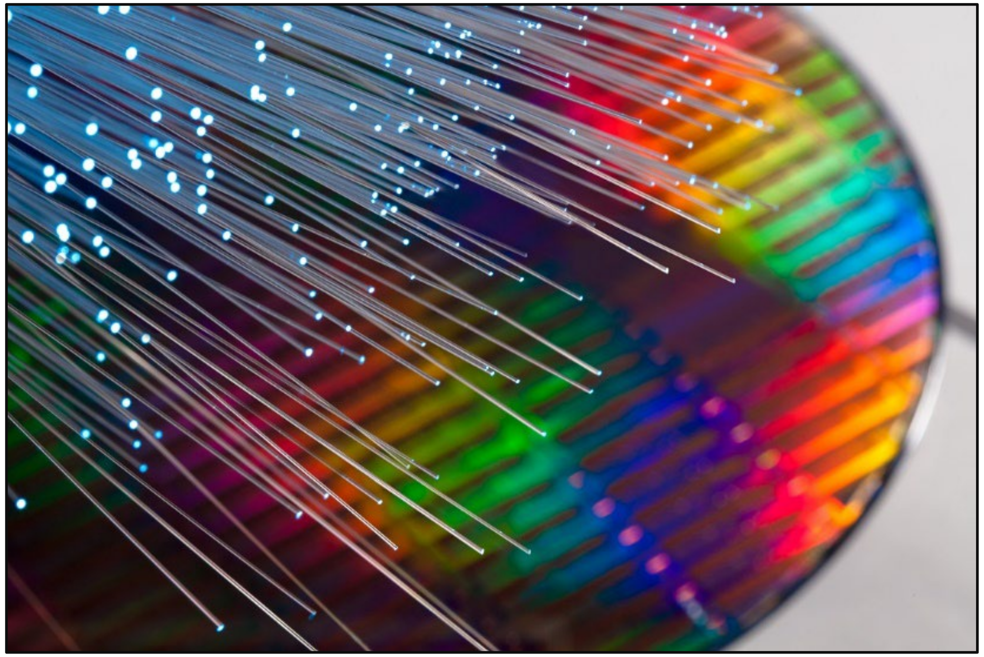
Many possible applications:

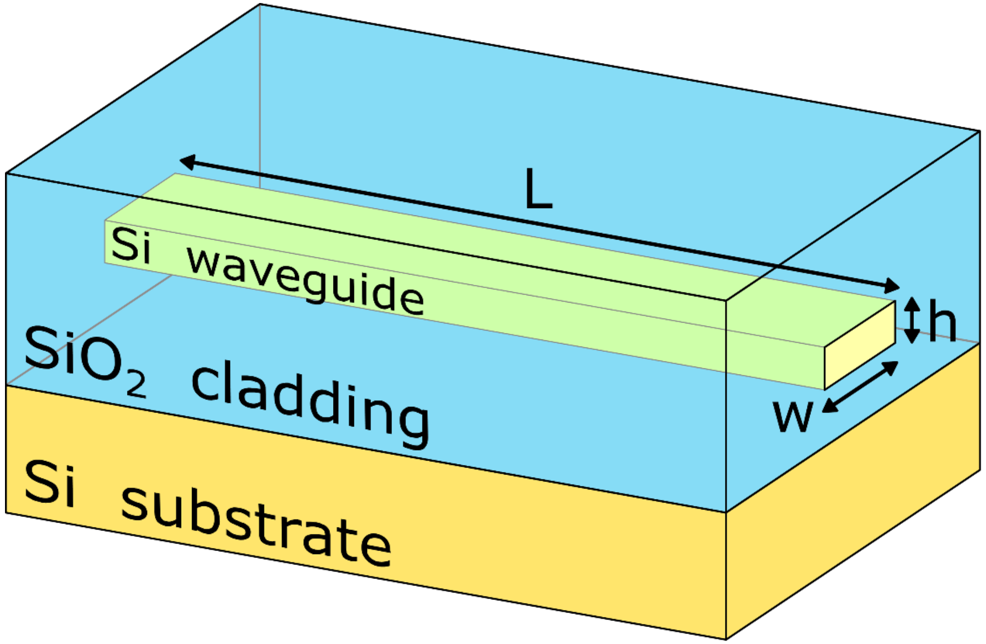
- Telecommunications
- Datacenter interconnections
- Sensing
- Neural networks
- Quantum computing

A wide spectrum of applications



Silicon Photonics





- Integrated optical circuits fabricated in a CMOS-compatible Silicon-based process.
- Compatible with optical trasmissions at 1550nm and 1300nm.
- High scalability thanks to excellent confinement properties of Silicon-on-Insulator waveguides.

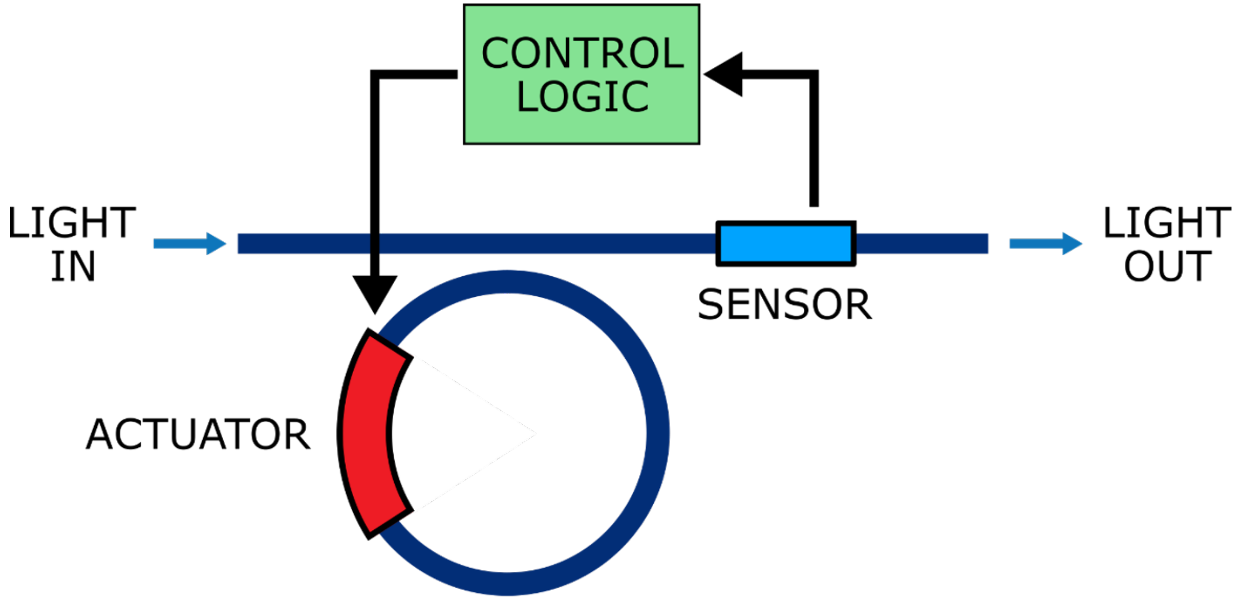
Example: detuning of a ring resonator

- Temperature sensitivity:

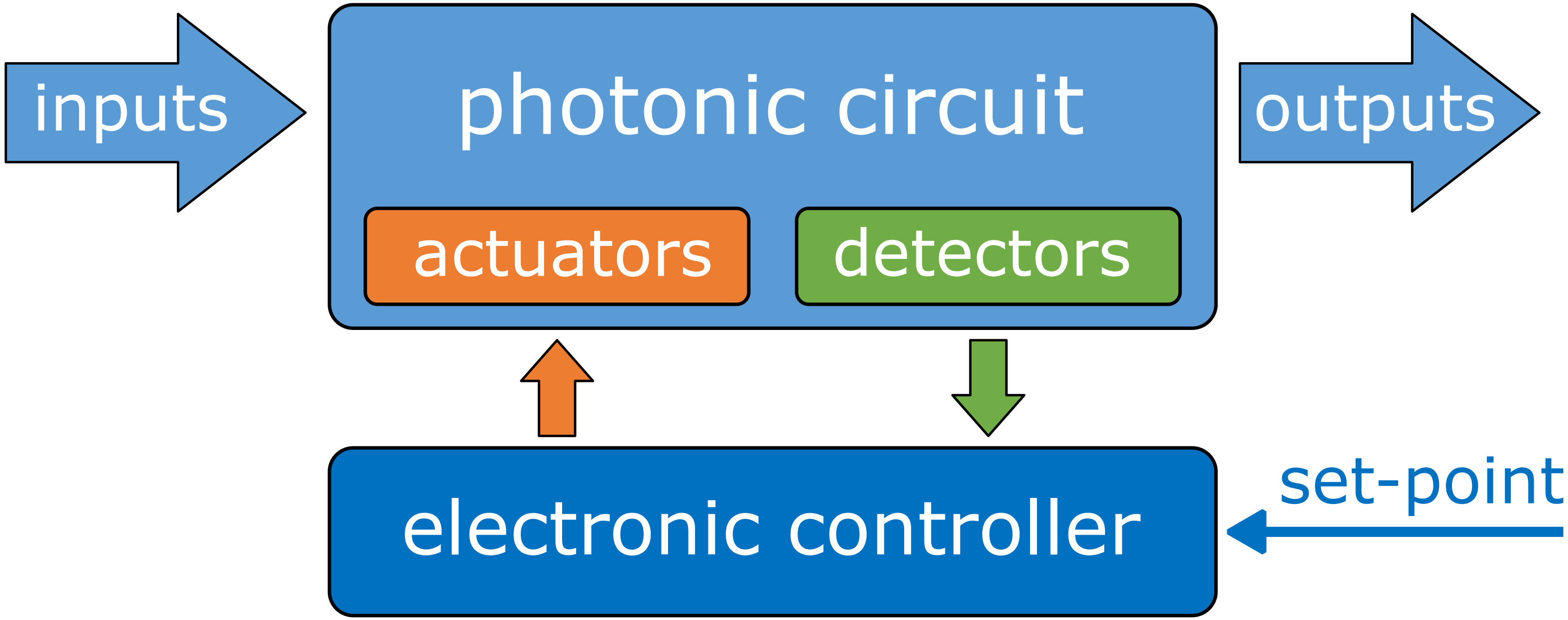
  $\Delta T = 10K \rightarrow$ $\Delta\lambda = 800pm$, $\Delta f = 100GHz$

- Sensitivity to fabrication tolerances:

  1 nm waveguide width mismatch $\rightarrow$ $\Delta\lambda = 800pm$, $\Delta f = 100GHz$



Electronic control of photonic circuits is needed to ensure stable and reliable operations!



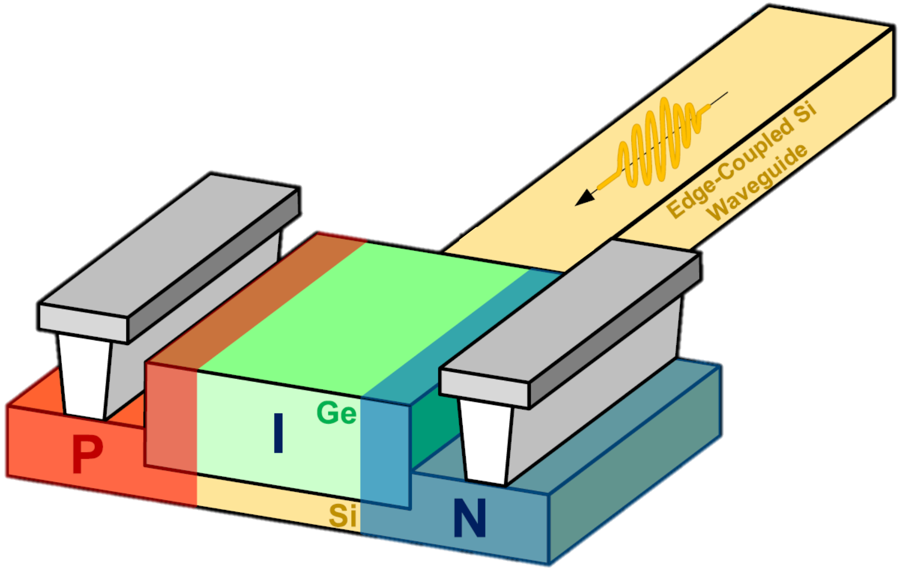
<u>The detectors:</u>

- must measure the working condition of the photonic chip.
- must be compatible with the technology.
- should introduce as low losses as possible.
- should have a readout time of few milliseconds.

Integrated light detectors

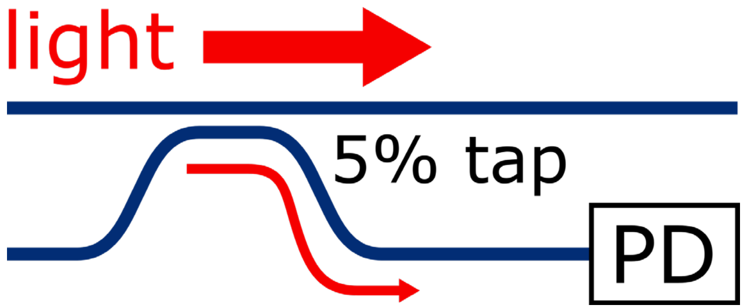
<u>Germanium photodiode:</u>

- Standard light sensor in Silicon Photonics.
- High sensitivity (0.7 A/W) and high speed (50 GHz).
- It requires to tap a small fraction of light from the main path to measure it.



<u>Tapping light is not always possible:</u>

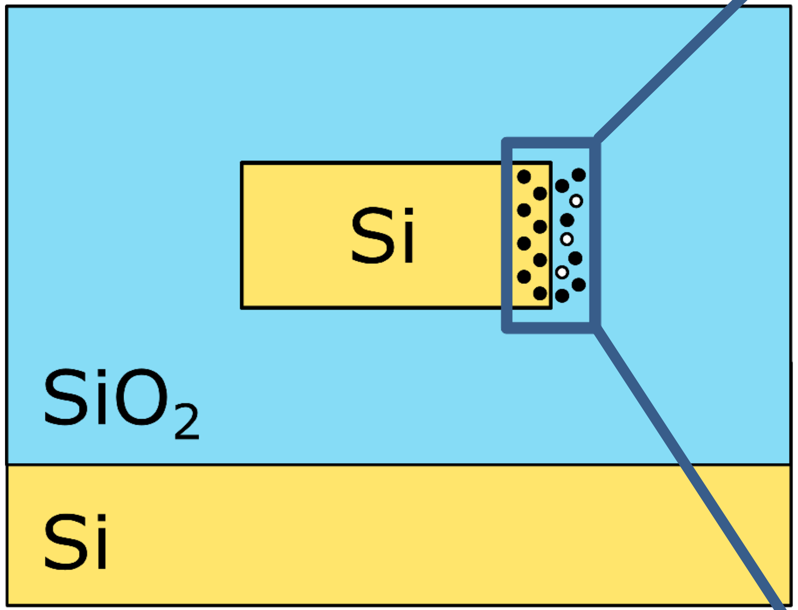
- When the number of detectors increases, the power loss becomes unacceptable.
- Each measurement slightly perturbs the optical properties of the propagating beams.

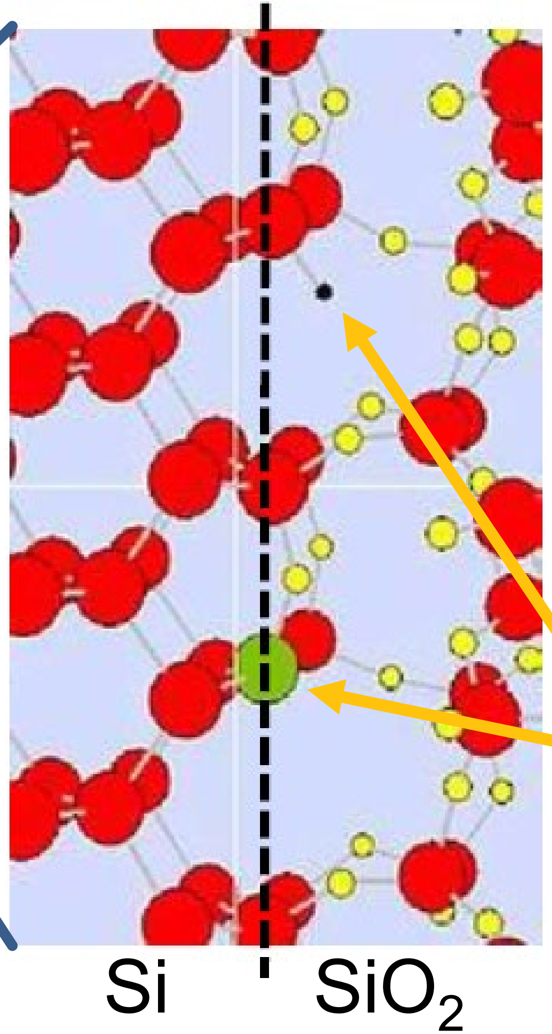


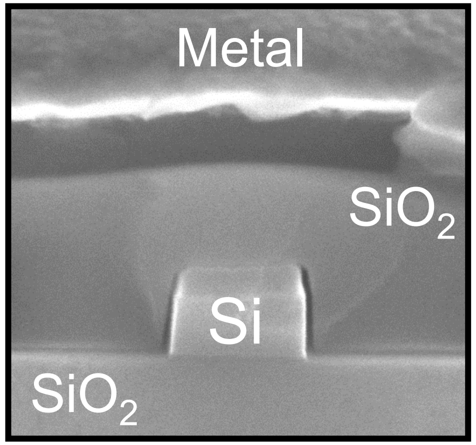
<u>"Transparent" light sensors must be developed to overcome these limitations.</u>

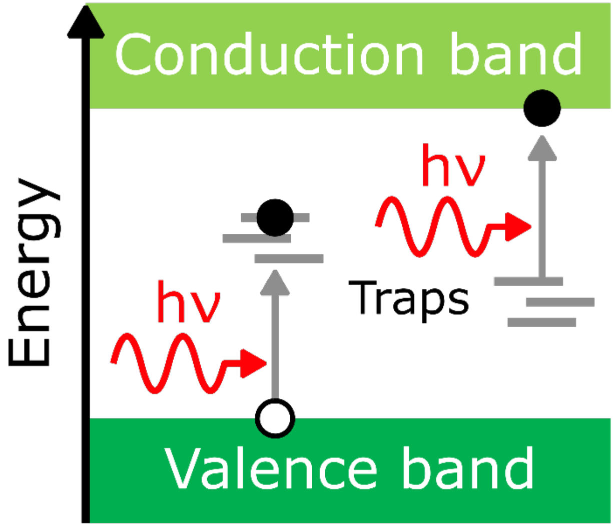
Defect-mediated free carriers generation

Surface-state absorption (SSA)



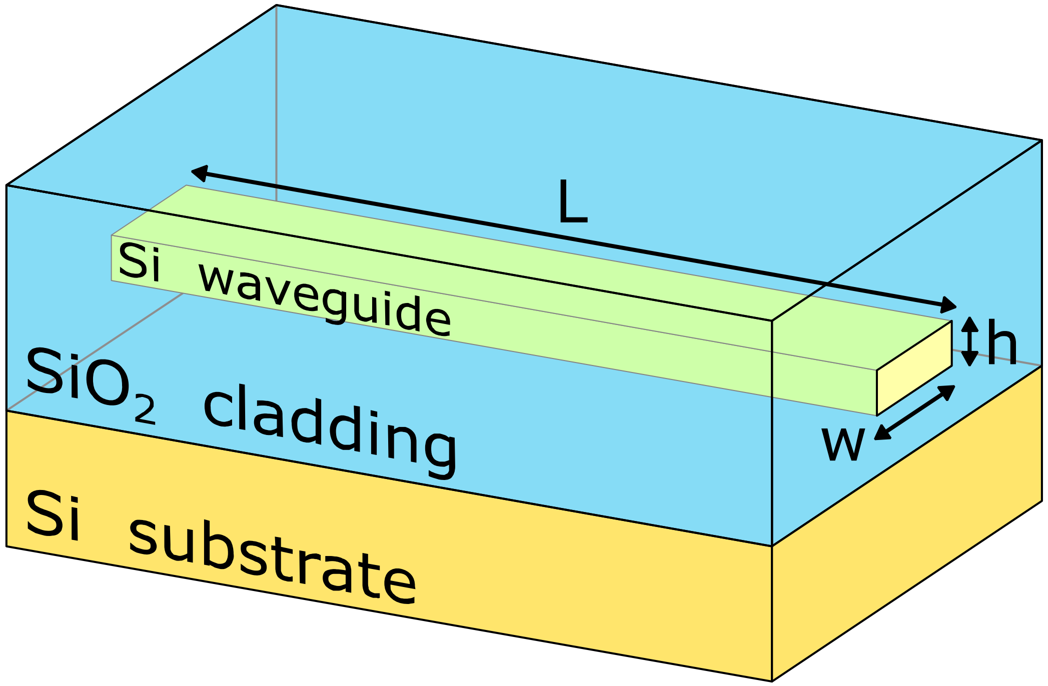






This phenomenon is responsible for the intrinsic propagation losses of the WG.

ContactLess Integrated Photonic Probe (CLIPP)



- The silicon waveguide behaves as a resistor:

$$G_{WG} = q \cdot \mu \cdot p \cdot \frac{h \cdot w}{L}$$

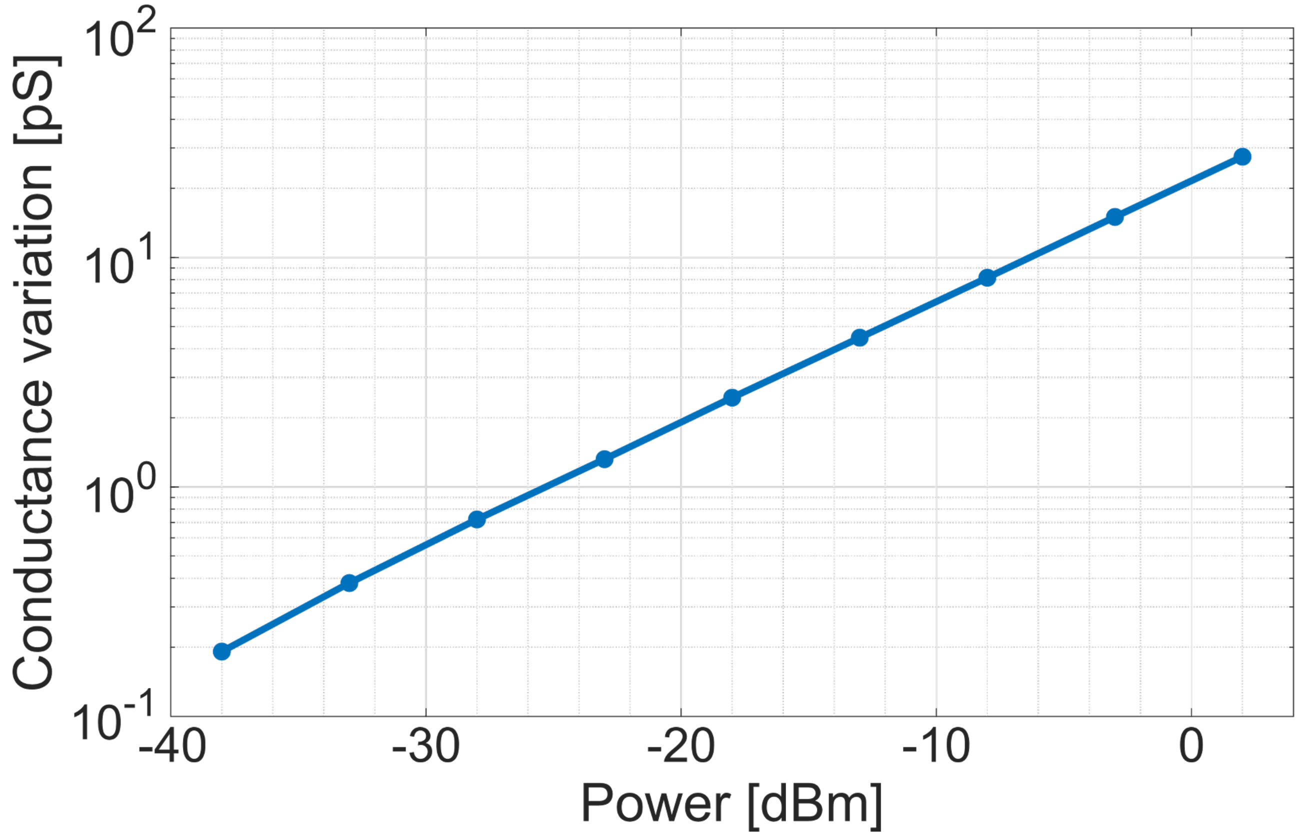
- The presence of light increases the number of free carriers in the waveguide due to defect-mediated absorption of photons.

$$\Delta G_{WG} = q \cdot \mu \cdot \Delta p \cdot \frac{h \cdot w}{L}$$

$$\Delta p \propto k \cdot P_{opt}^{\eta} \quad \text{with } 0.5<\eta<1$$

F. Morichetti et al., IEEE JSTQE, 20, 4, 292-301 (2022)

ContactLess Integrated Photonic Probe (CLIPP)



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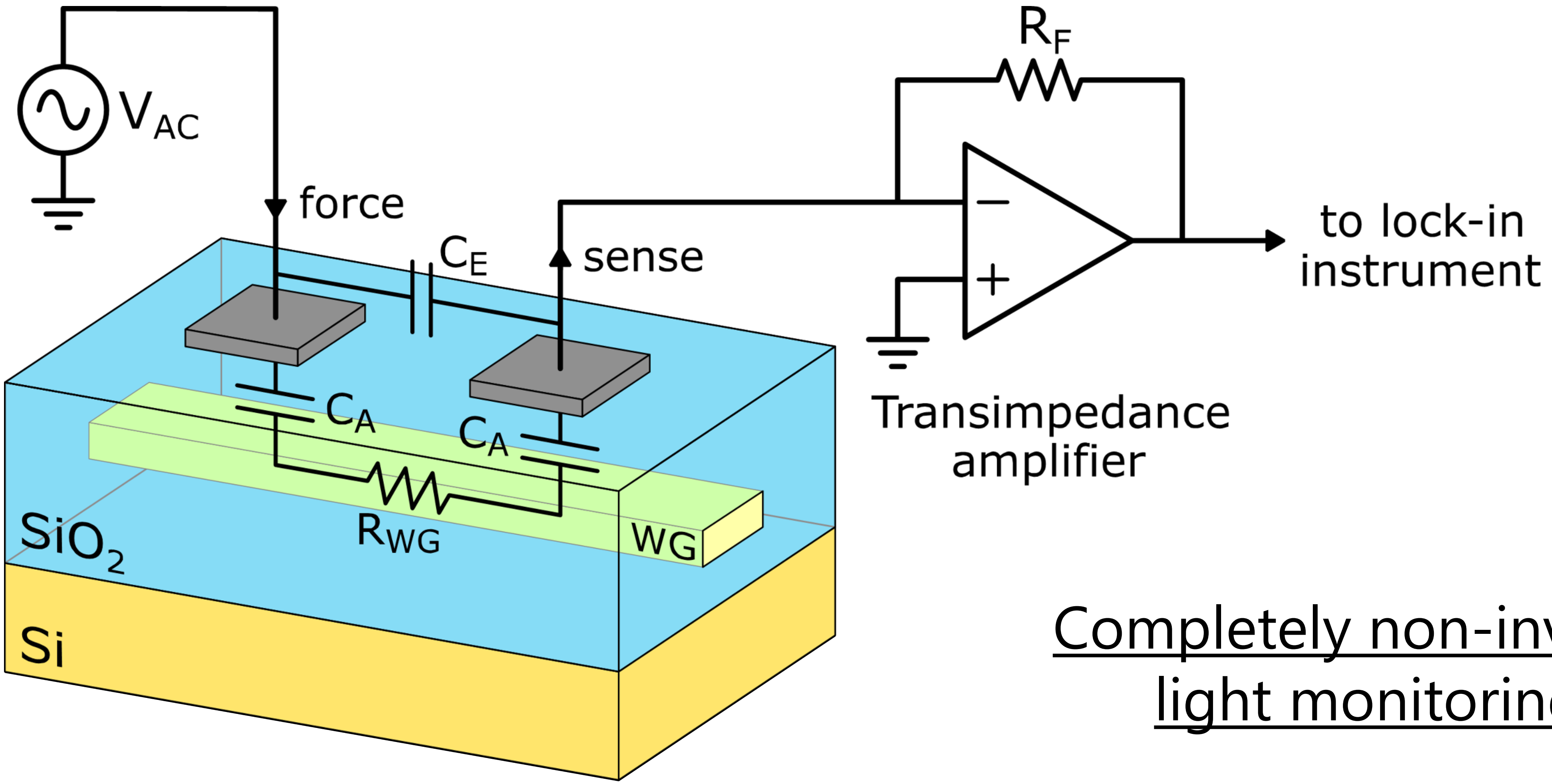
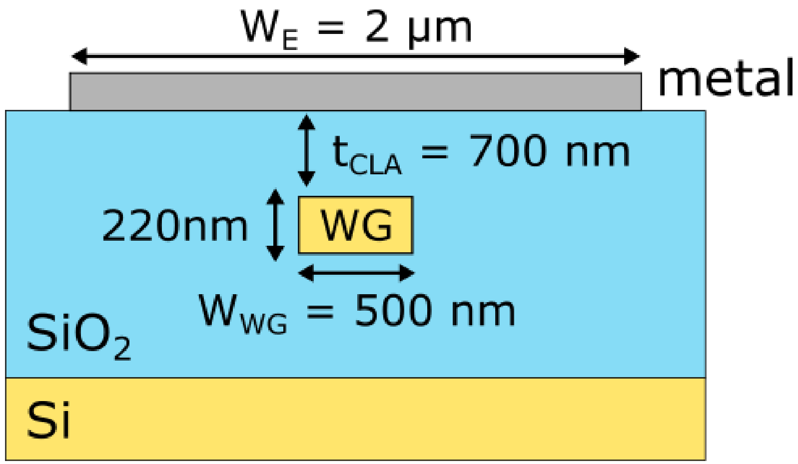
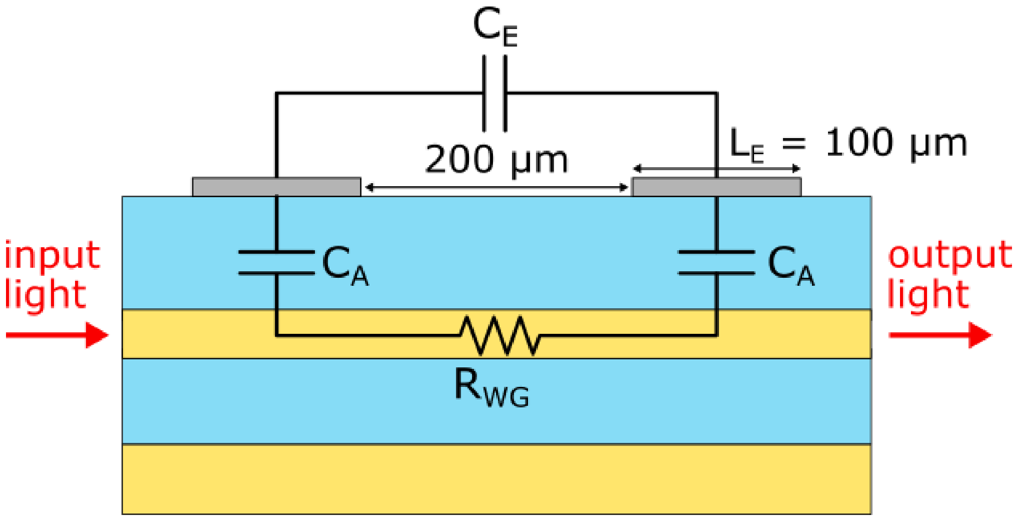
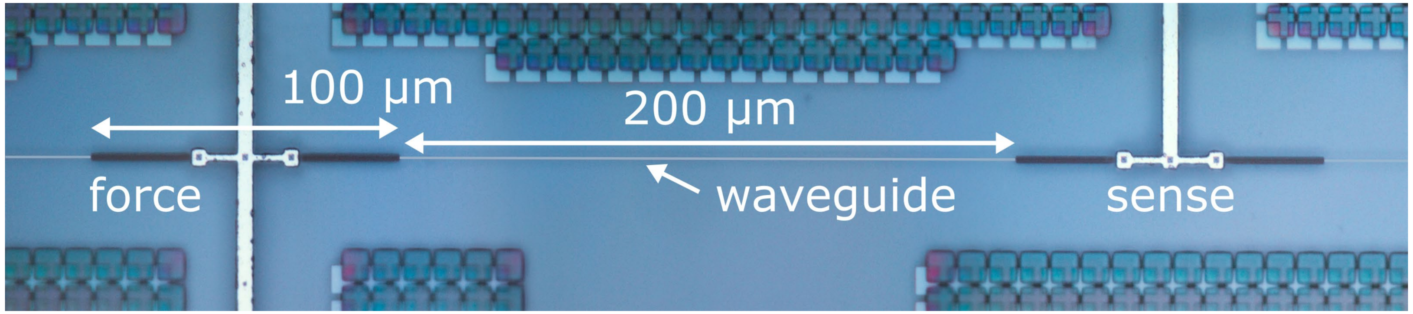


<u>Completely non-invasive light monitoring!</u>

F. Morichetti et al., IEEE JSTQE, 20, 4, 292-301 (2022)





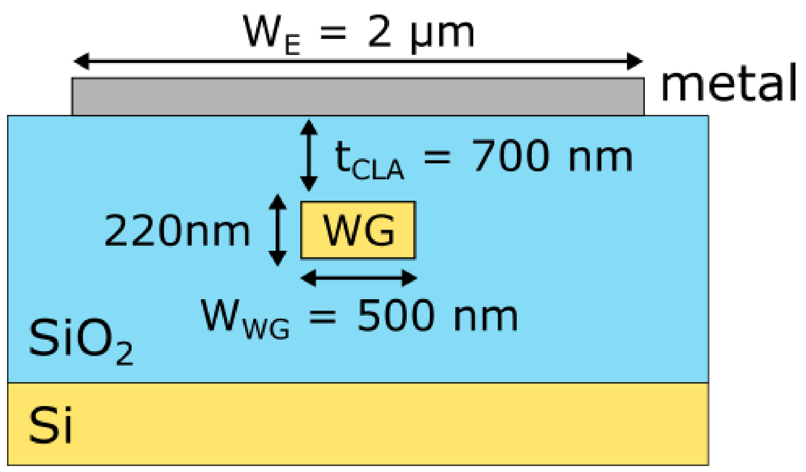


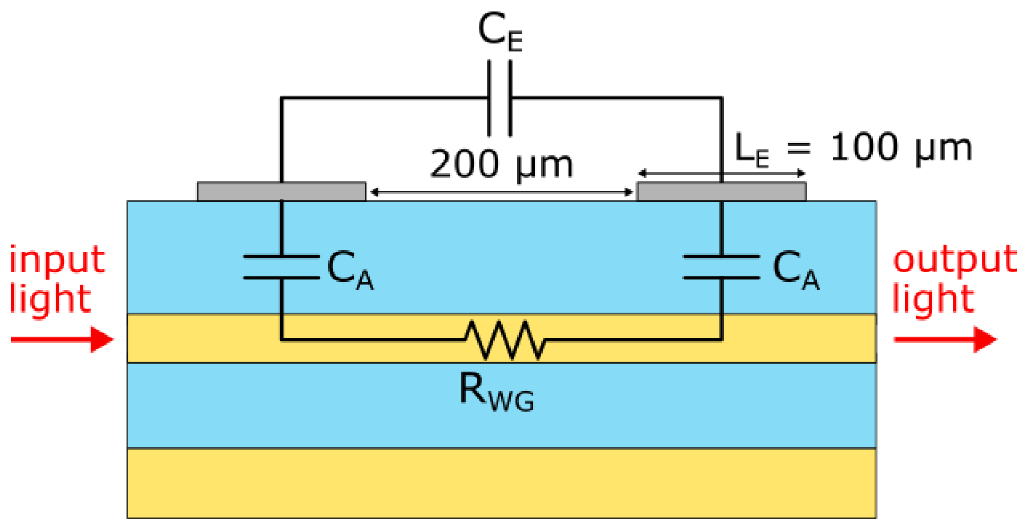
$$G_{WG} = q \cdot p \cdot \mu \cdot \frac{h \cdot w}{L} = 5\, nS$$

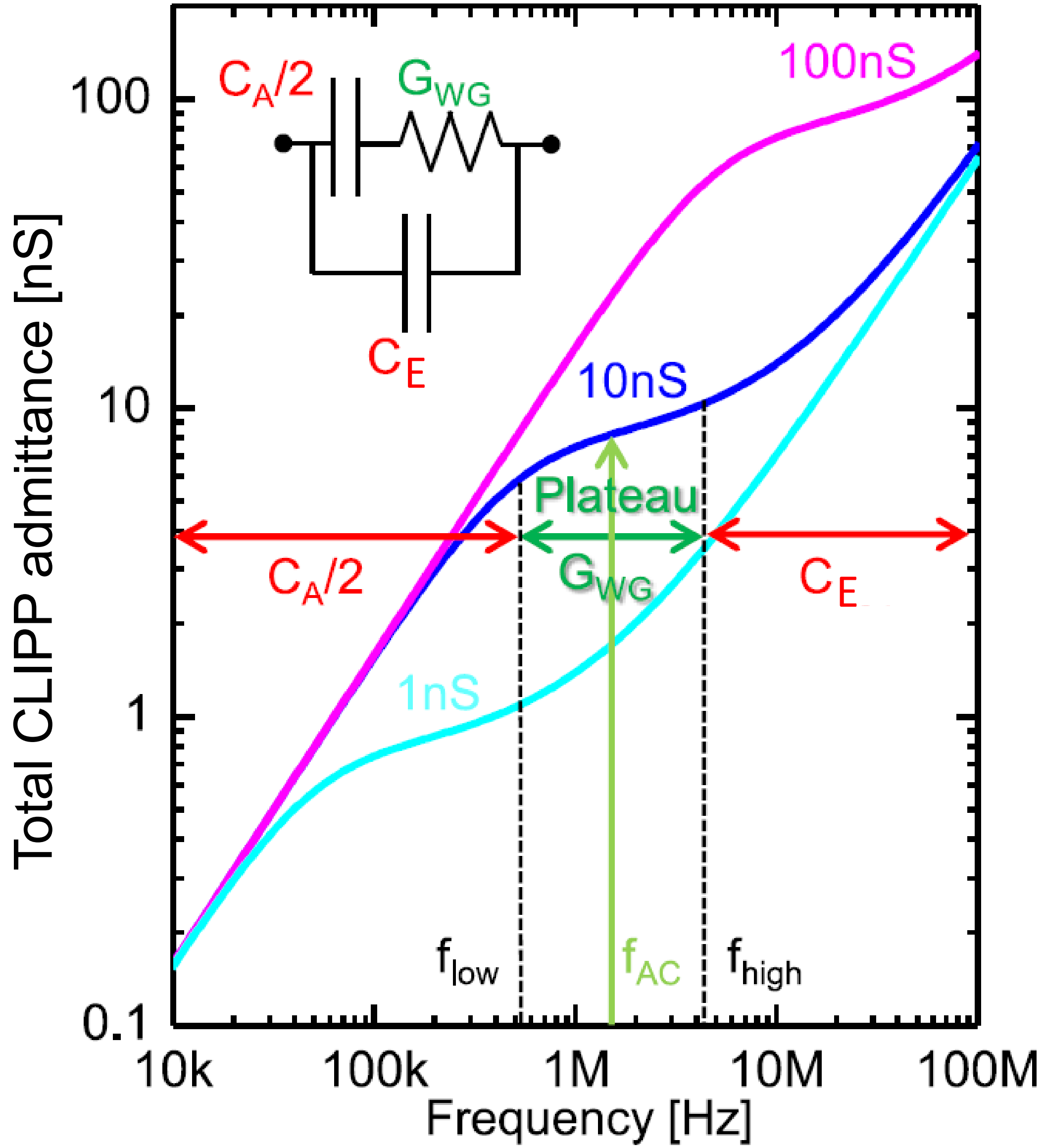
$$C_A = \varepsilon_0 \cdot \varepsilon_{ox} \frac{L_E \cdot (W_{WG} + 2t_{CLA})}{t_{CLA}} = 10\, fF$$

$$f_p = \frac{1}{2\, \pi\, R_{WG} \frac{C_A}{2}} = 40\, kHz$$

$C_E \approx 50\, fF - 500\, fF$ (layout dependent)

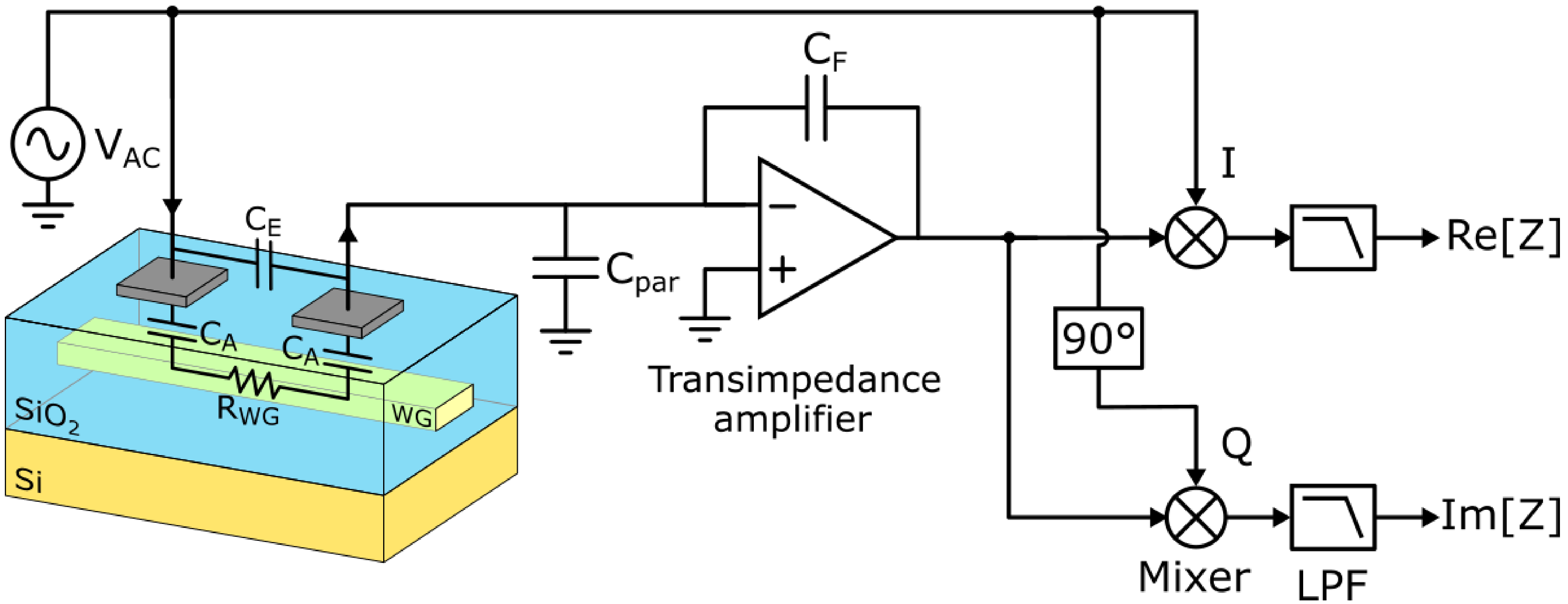

W_E = 2 µm
metal
t_CLA = 700 nm
220nm
WG
W_WG = 500 nm
SiO2
Si


C_E
200 µm
L_E = 100 µm
input light
C_A
C_A
output light
R_WG


C_A/2
G_WG
C_E
100nS
10nS
1nS
Plateau
C_A/2
G_WG
C_E
f_low
f_AC
f_high
100
10
1
0.1
10k
100k
1M
10M
100M
Total CLIPP admittance [nS]
Frequency [Hz]

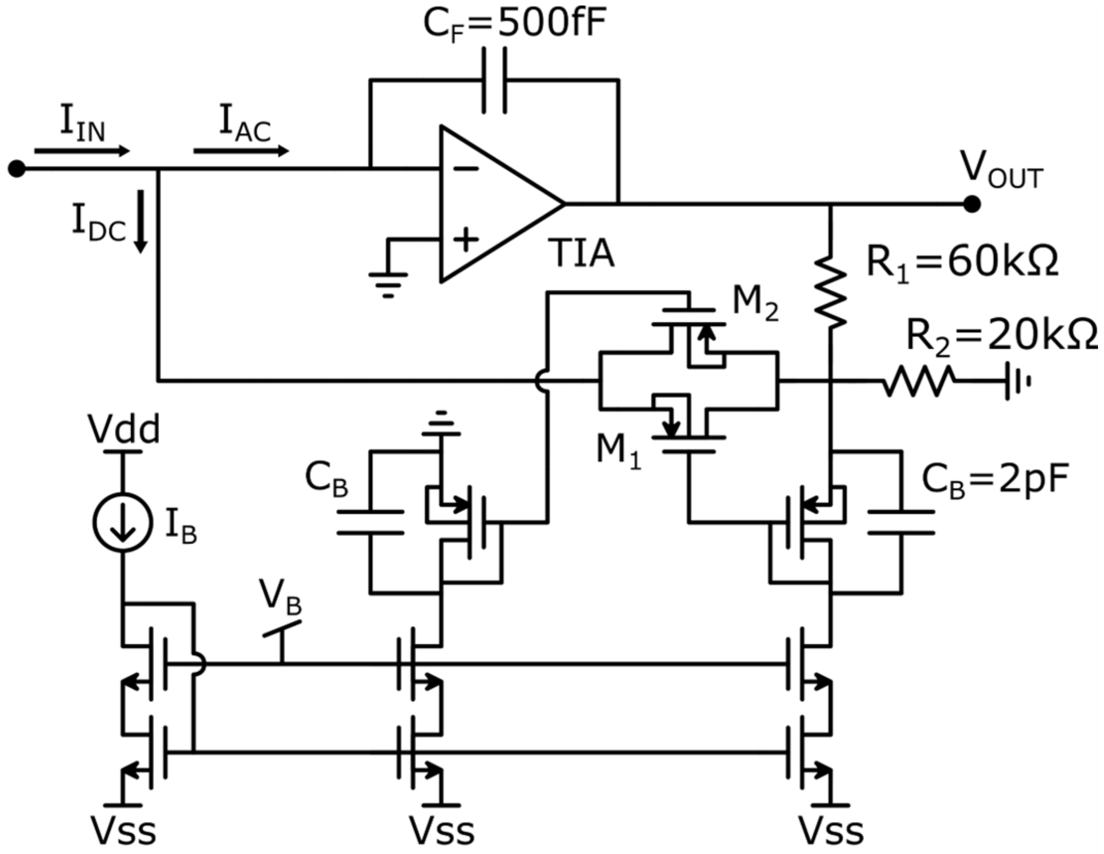
Lock-in detection scheme for admittance readout:

- Stimulus frequency higher than electrical pole
- Capacitive TIA to break bandwidth/noise tradeoff
- Extraction of real and imaginary part to reconstruct complex impedance



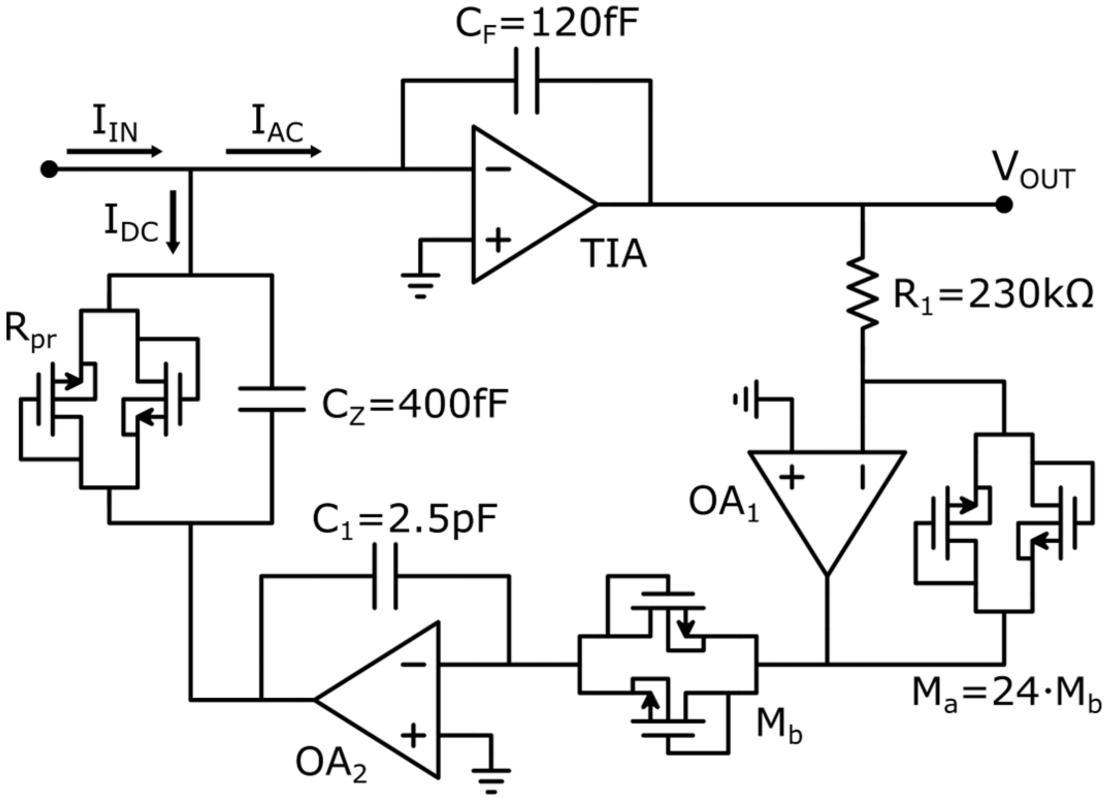
Integrated implementations

- Passive, low-power DC bias
- Prone to output offsets due to DC currents



Guglielmi et al., IEEE JSSC, 55, 8 (2020)

- Active low-frequency auxiliary feedback
- Area and power consumption

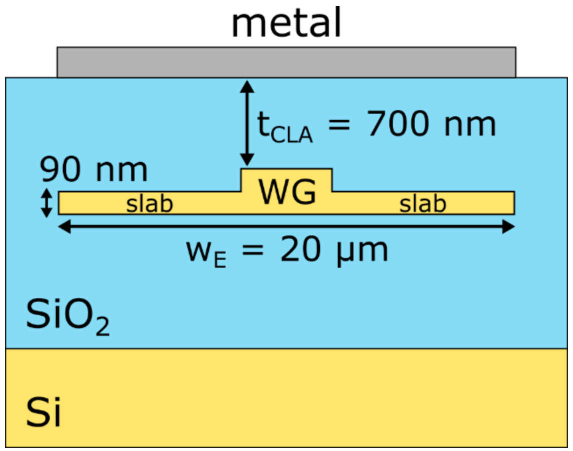


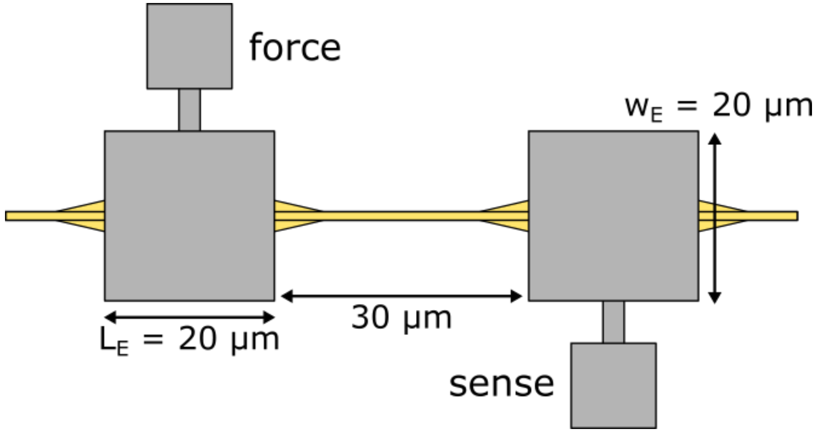
Zanetto et al., IEEE SSCL, 3, 246-249 (2020)

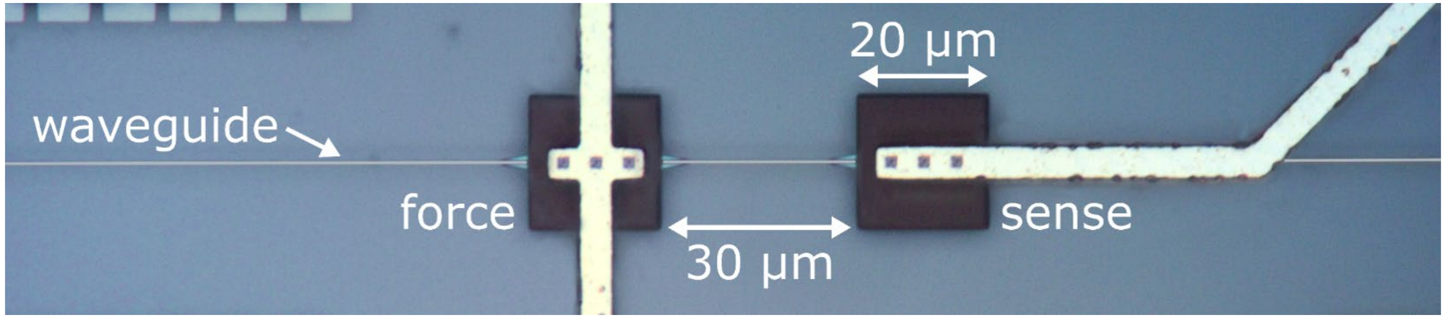
A short detector is better than a long one:

$$\Delta G_{WG} = \Delta p \cdot q \cdot \mu \cdot \frac{h \cdot w}{L}$$

- True only because the detector admittance is dominated by C_E
- Short detector = lower WG resistance
- To keep the same readout frequency, increase the access capacitance with slabs under the electrodes.

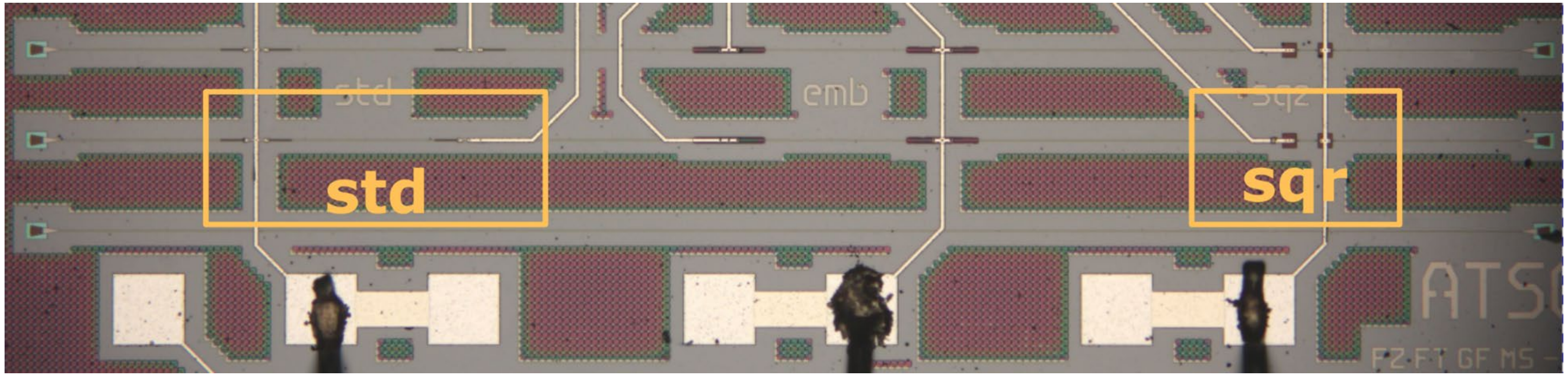




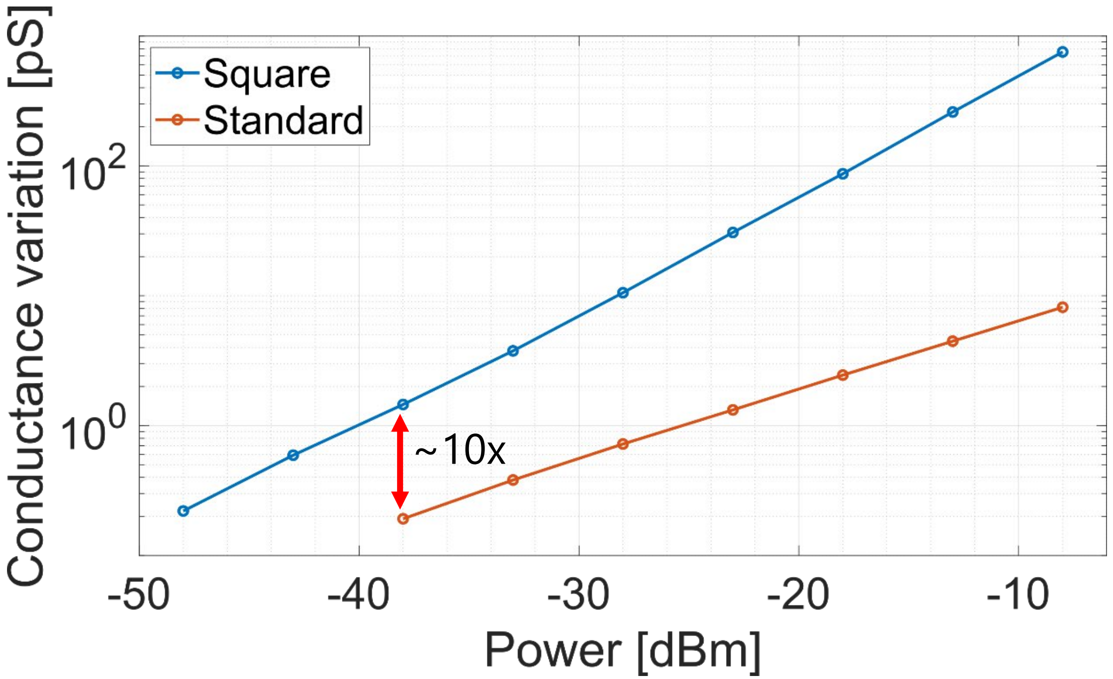


Experimental validation

Light in



Light out

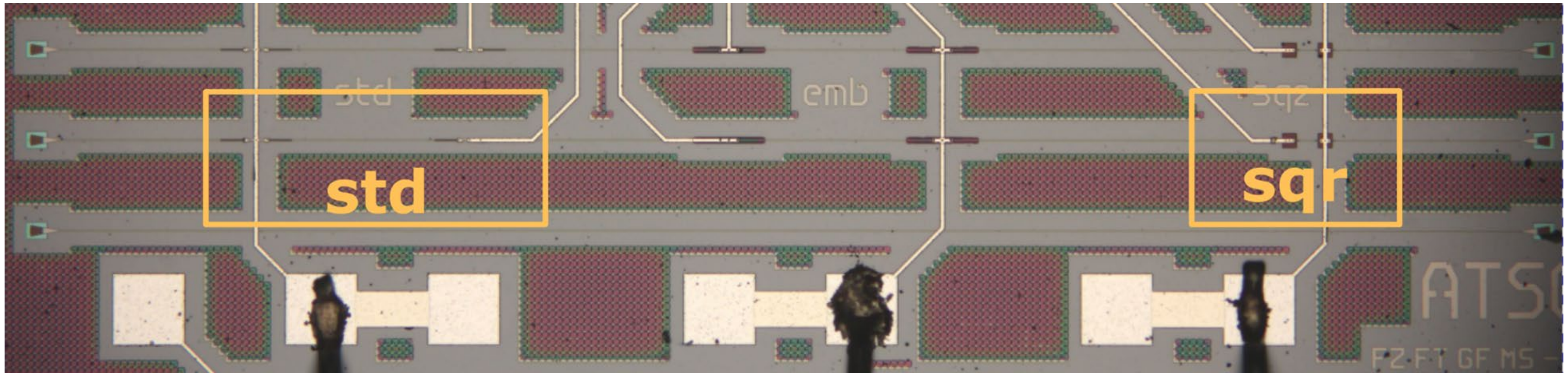


- ~10x conductance variation for the same optical signal.
- ~6x smaller sensor footprint.
- Detection of light signals down to -50 dBm (10 nW)

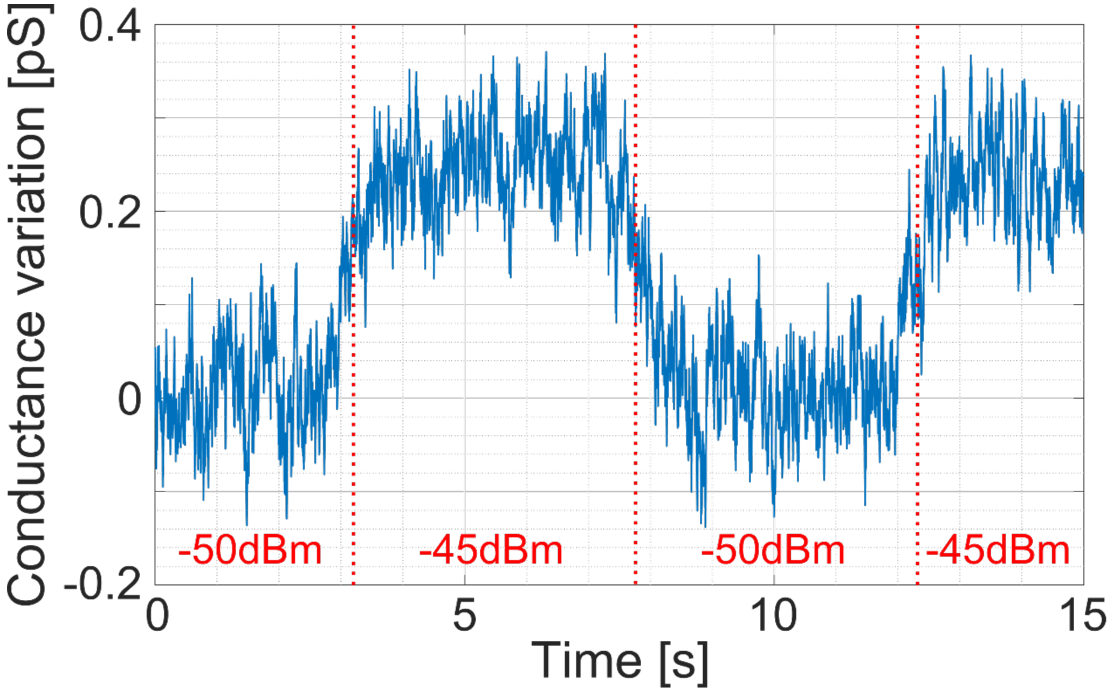
V. Grimaldi et al., PRIME conference, 285-288 (2022)

Experimental validation

Light in



Light out



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- Detection of light signals down to -50 dBm (10 nW)

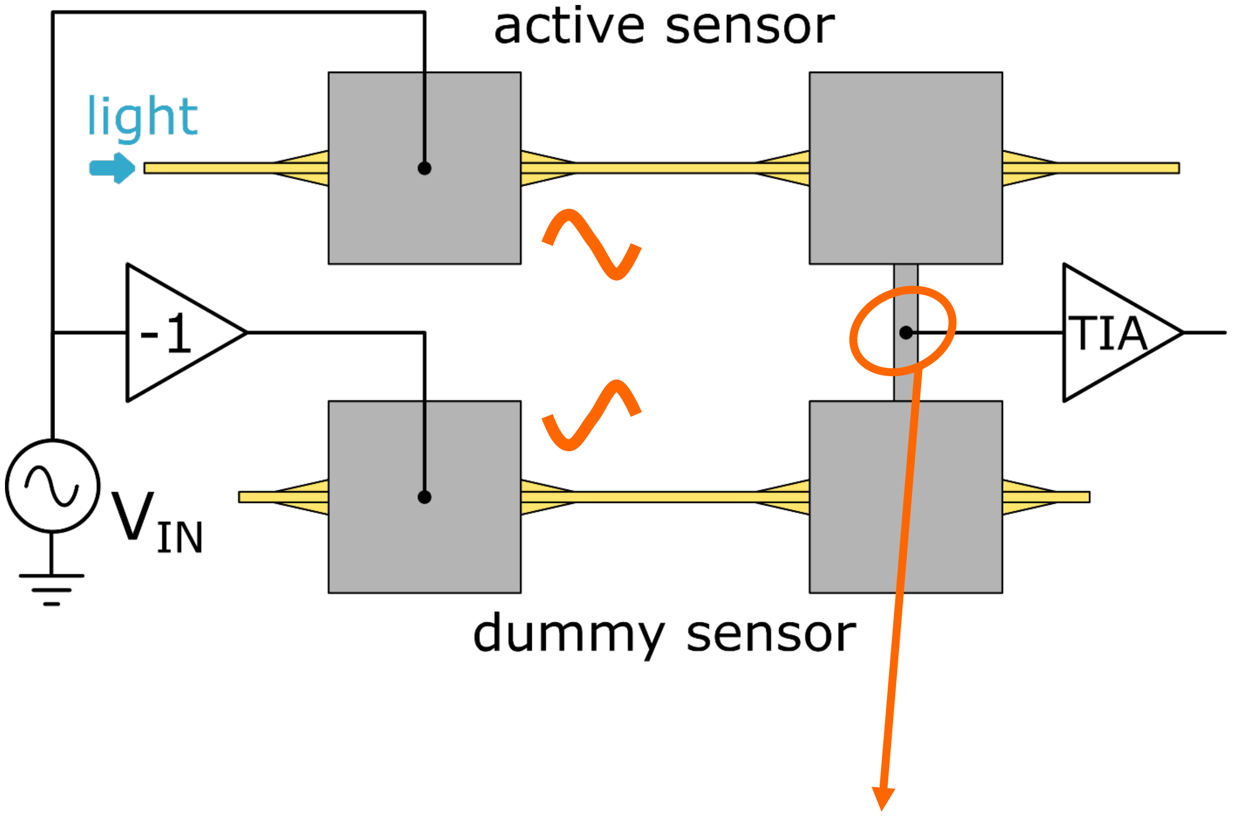
V. Grimaldi et al., PRIME conference, 285-288 (2022)

Differential sensor topology

Main CLIPP problems:

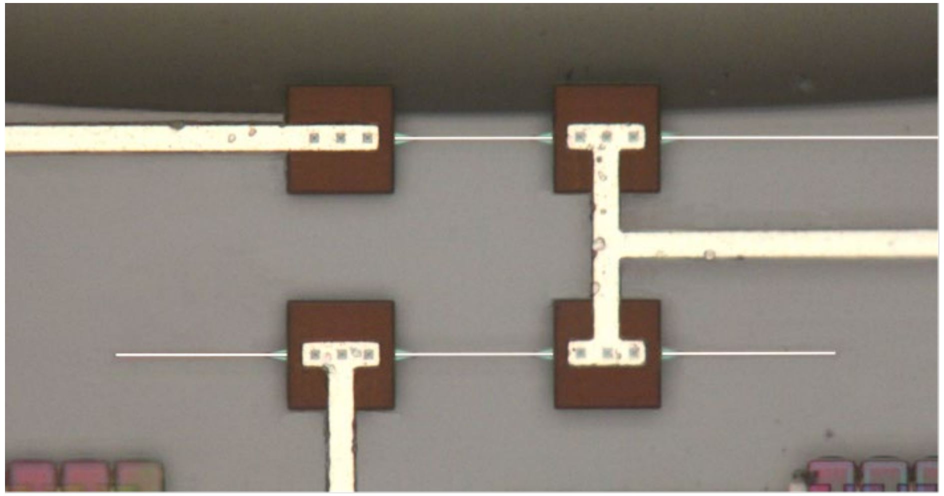
- The coupling between the electrodes generates a current much larger than the small variations to be measured.
- Sensitivity to temperature variations.
- Crosstalk between CLIPPs on different waveguides due to light in the oxide and substrate.

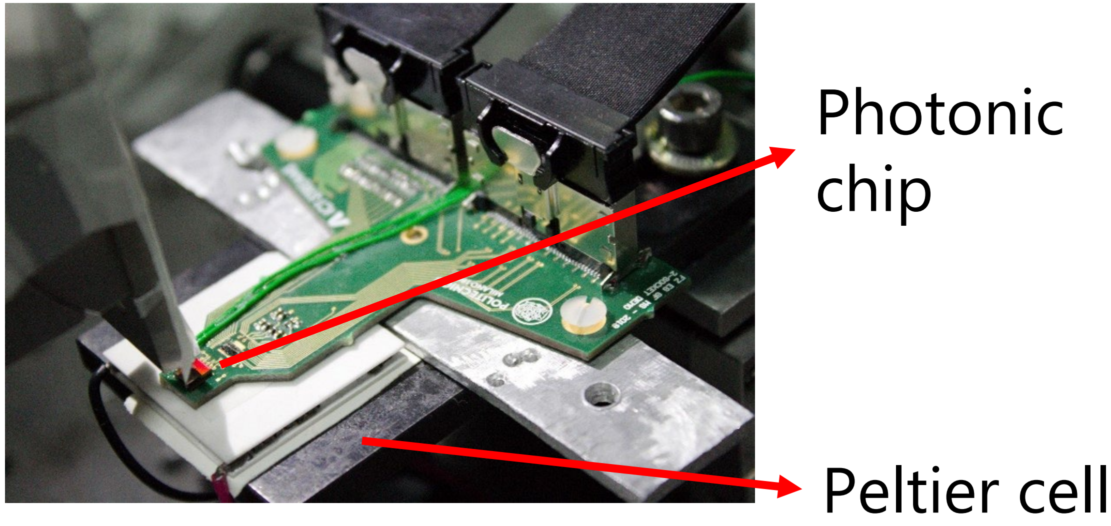
Differential topology to solve them all!

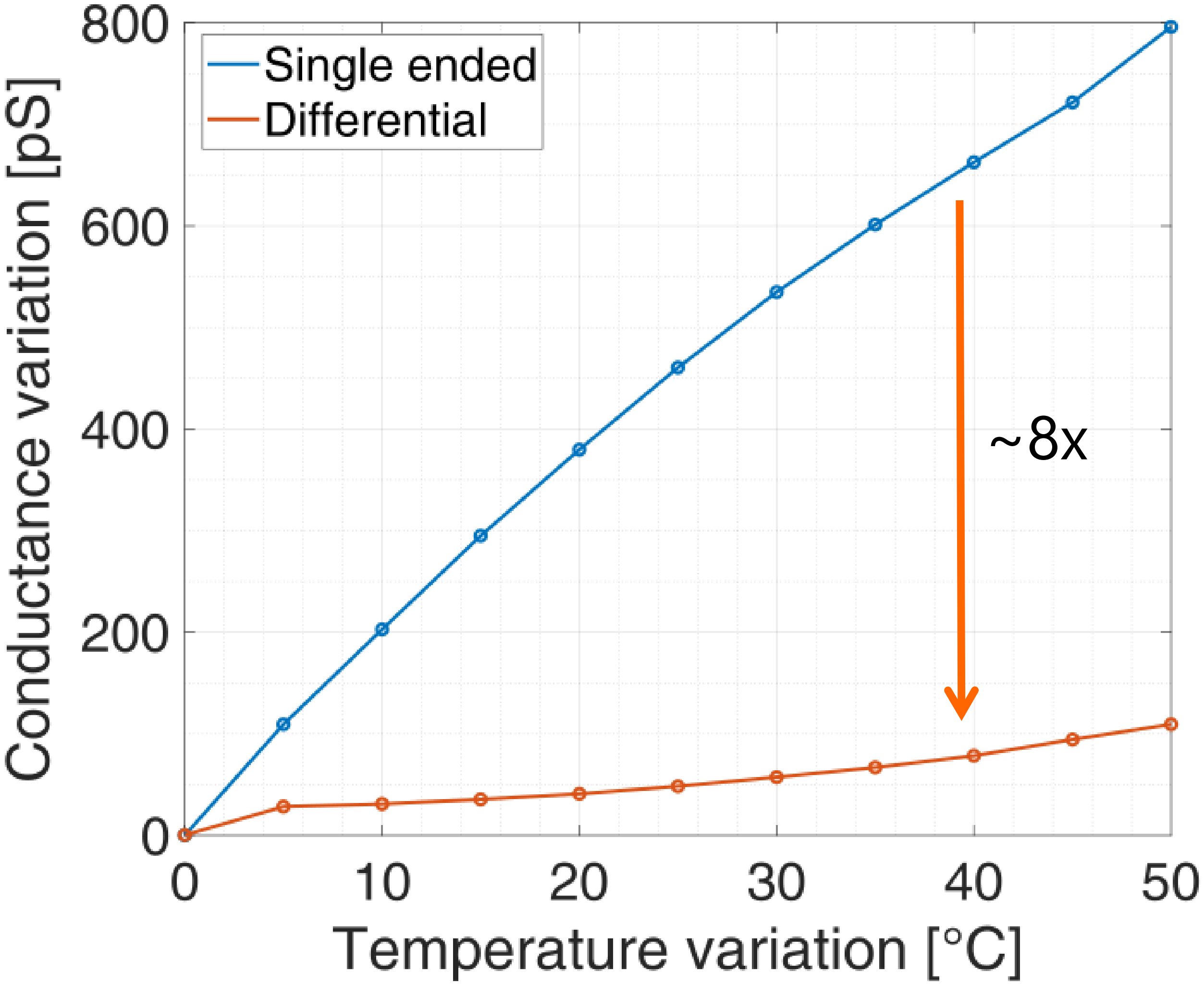


Any commod-mode current is steered away from the virtual ground of the TIA.

Experimental demonstration



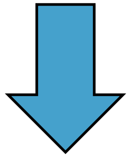




Increasing the detector sensitivity

The CLIPP sensor has good sensitivity but:

- In some applications sensors that can detect even weaker light signals are needed.
- The CLIPP performance greatly relies on the use of a very low-noise custom front-end electronics.
- The sensor readout is not easy since a multichannel lock-in amplifier operating at around 1 MHz is needed.

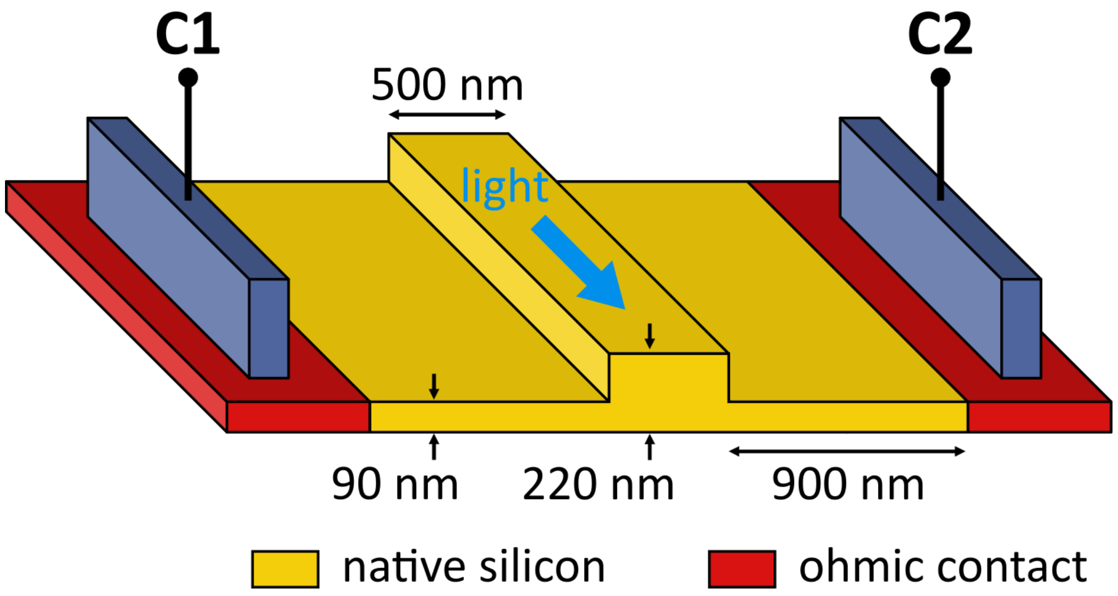


Other sensor topologies can be studied to improve and simplify light detection while keeping the advantages of CLIPPs.

Waveguide-integrated light sensors

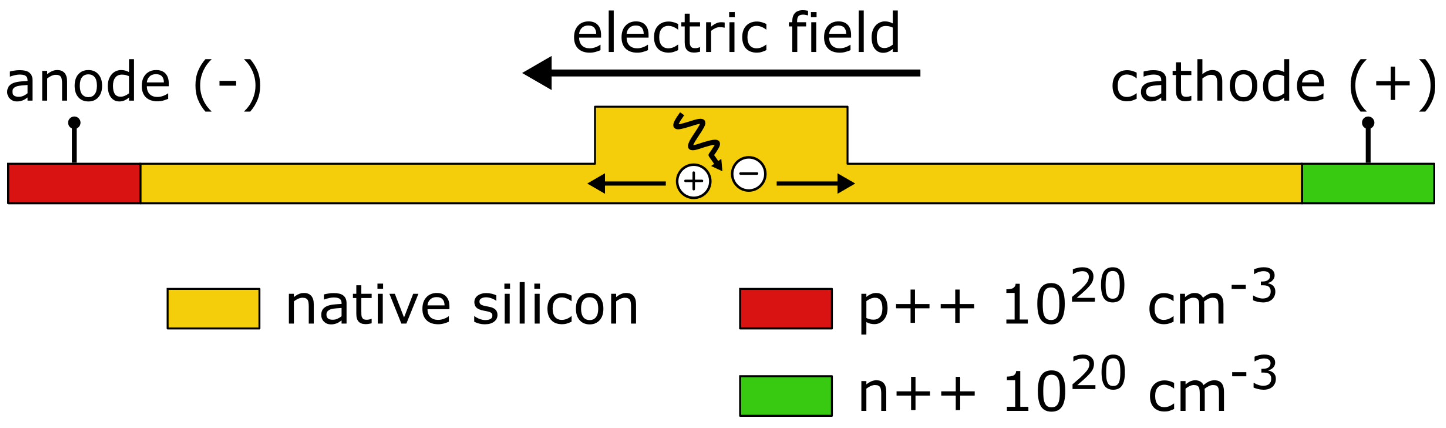
- Photonic technologies allow to dope the waveguide core to design opto-electronic devices like modulators and attenuators.
- The doping is needed to obtain the desired optoelectronic behavior and to access to the waveguide electrical properties.
- This additional processing step can be used to design WG-integrated sensors.

Low frequency operations and possibly higher sensitivity than CLIPPs.



Light is confined in the center; the contacts are far away and the core is not doped not to introduce additional losses.

Transparent p-i-n photodiode

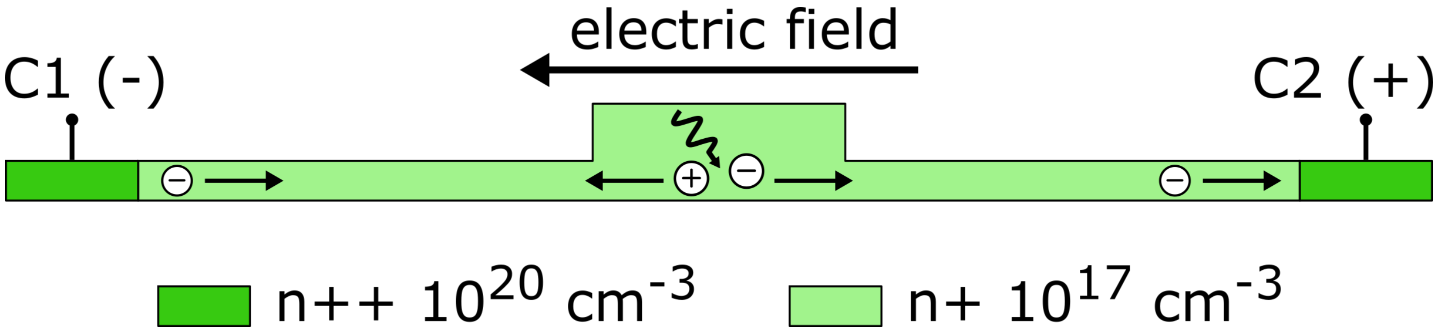


The core is depleted of free-carriers due to the large electric field in the p-i-n structure.

- The photogenerated (due to SSA) electron-hole pairs are rapidly separated by the electric field in the device and collected by the ohmic contacts.
- A current pulse is produced each time an e-h pair is generated and travels through the WG. The pulse ends when the carriers reach the contacts.
- The total current in the device is the sum of all the pulses per second, whose average number is determined by the photogeneration rate (photocarriers/s) G_{OPT}:

$$I_{PD} = q \cdot G_{OPT}$$

Doped photoconductor



The central region is now full of free-carriers as defined by the doping level.

- The drift velocity of the generated e-h is defined by their mobility inside the device. It is usually very different for e- and h+, especially in thin structures like WGs.
- To keep charge neutrality during the collection of carriers, an e- is injected from C1 each time another e- reaches C2, until one e- recombines with the h+ (recirculating current mechanism). This extends the duration of each current pulse.
- The total current in the device is thus increased compared to the pin diode due to pulses accumulation. The amplification factor is called photoresistive gain G_{PR}:

$$I_{PR} = q \cdot G_{OPT} \cdot G_{PR} = I_{\mathrm{PD}} \cdot G_{PR}$$

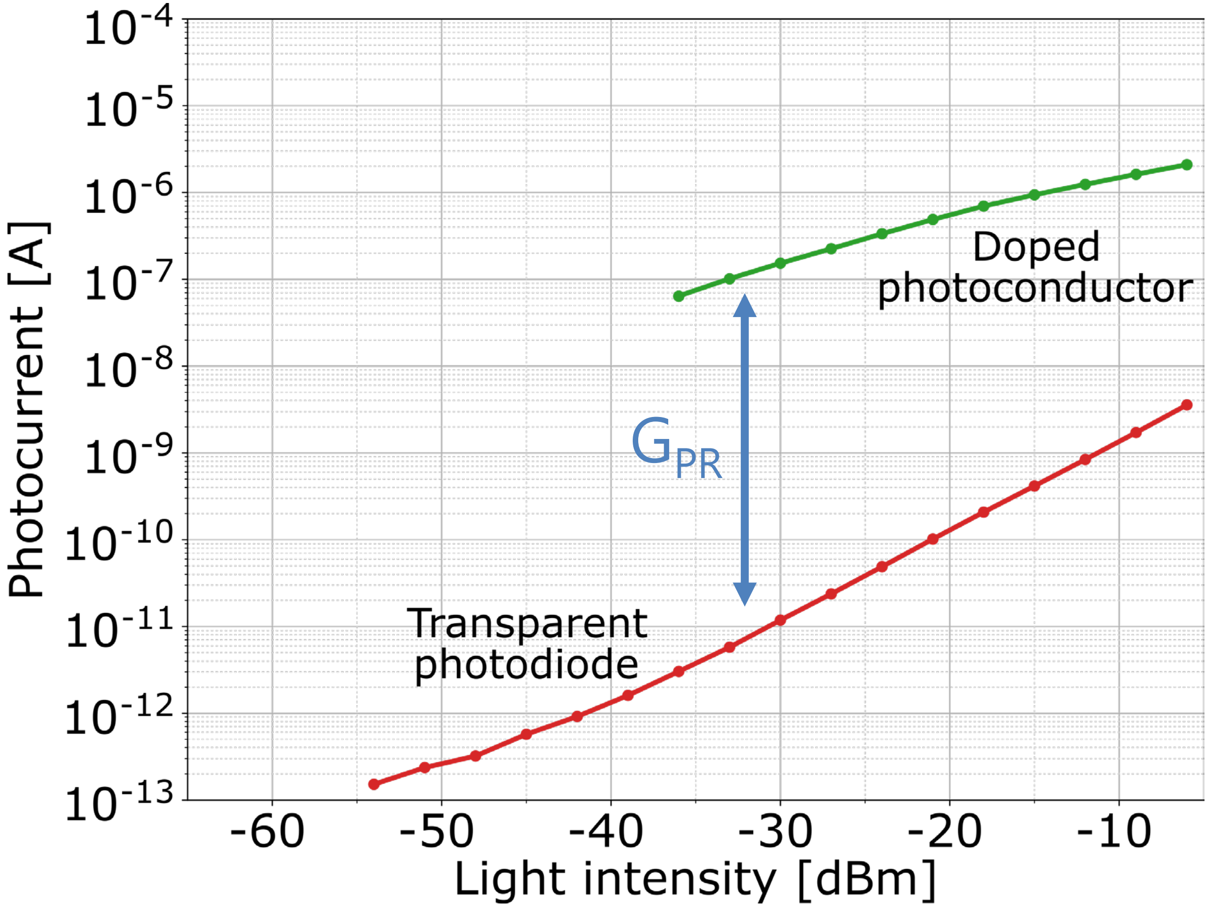
Photoconductive gain

- If a p-i-n diode and a photoconductor have the same geometry, the latter generates a much larger photocurrent, easier to be detected.

- It can be shown that:

$$G_{PR} \propto \frac{\tau_{LIFE}}{\tau_{TRANSIT}}$$

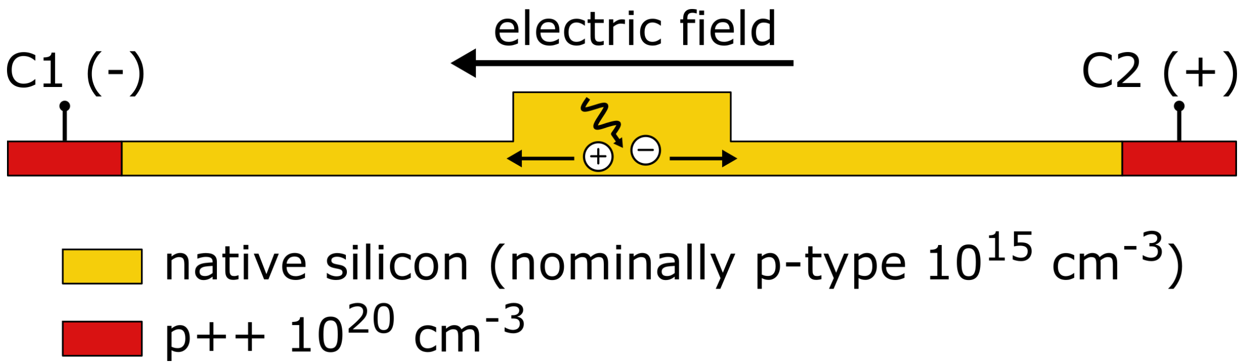
where τ_{LIFE} is the lifetime of the photogenerated e-h pair and $\tau_{TRANSIT}$ is the time needed by the fastest of the two carriers to go from one contact to the other.

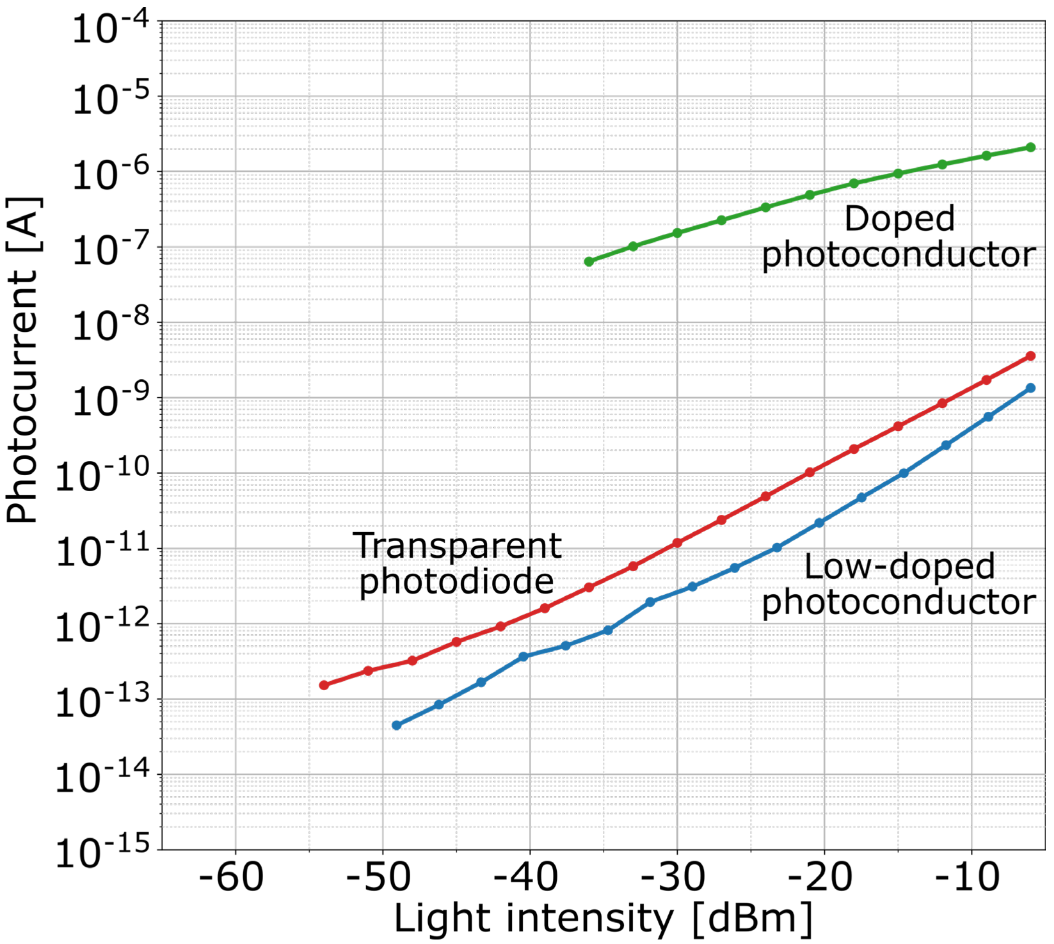


Low-doped photoconductor

- Transparent photoconductors found in literature usually feature a lightly doped WG-core.
- However, it is well known that the lifetime of a photogenerated free-carrier in a semiconductor is inversely proportional to the doping of the material.

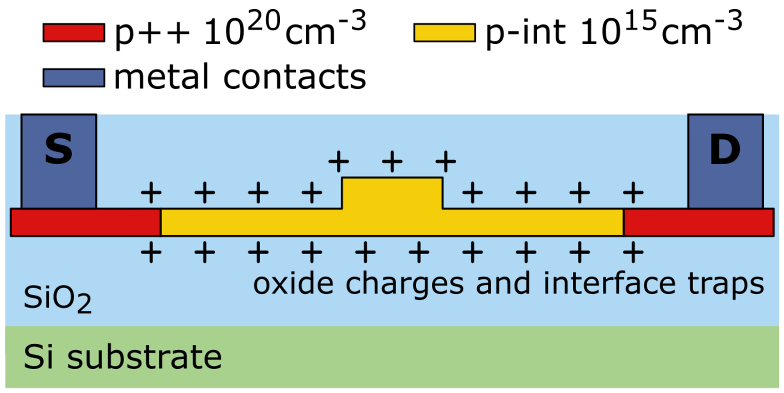
<u>A photoconductor where the WG is not doped should have higher photoconductive gain!</u>

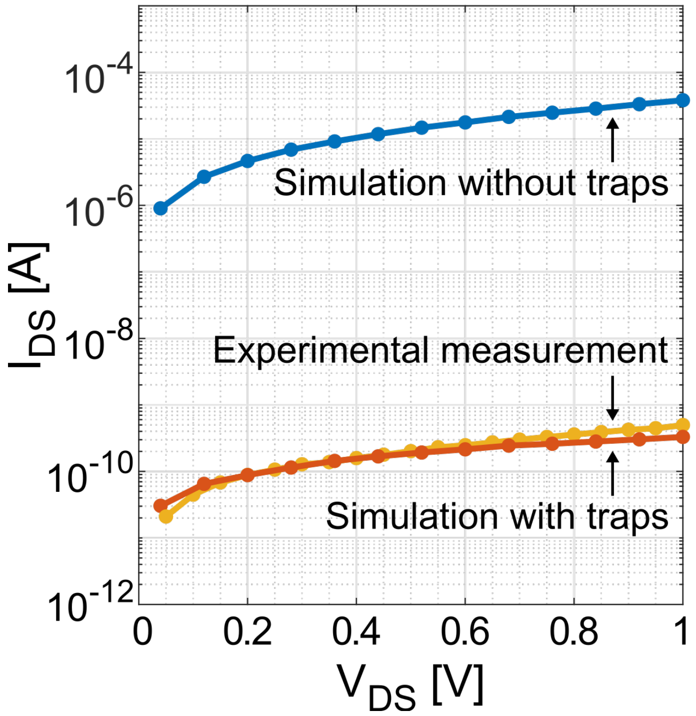


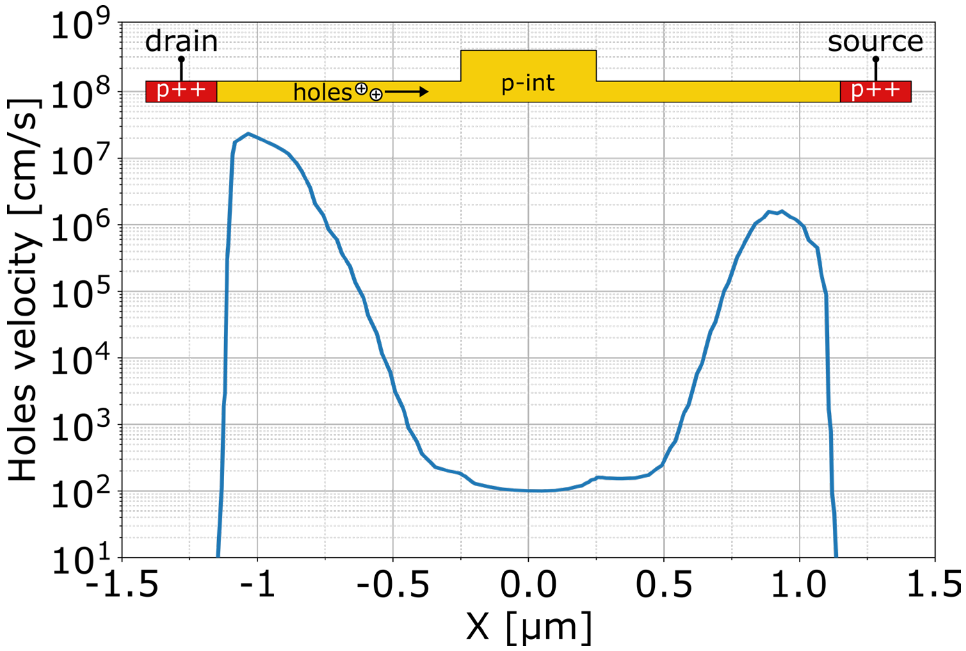


$G_{PR} < 1$!!!
What's going on here?

- The waveguide has low doping and a very thin structure with a high surface-to-volume ratio, therefore surface effects have a huge impact on the conduction!
- The same charges, defects and traps responsible for sub-bandgap photogeneration also deplete the WG from free-carriers and slow down the motion of the photo-generated ones, increasing the transit time!

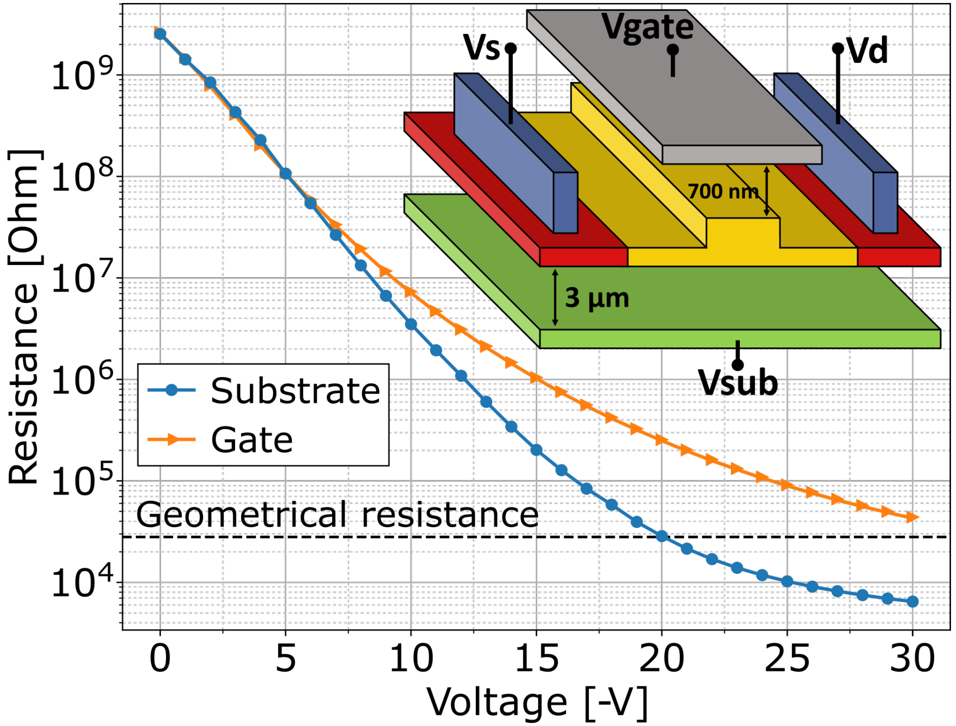


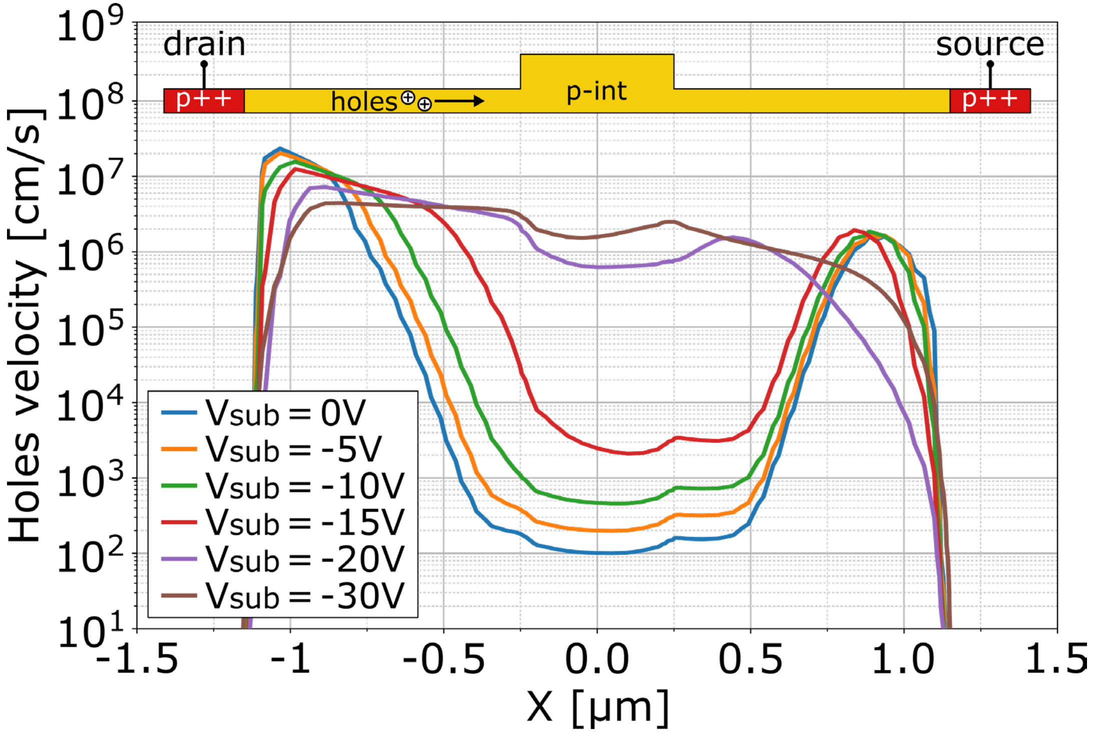




Charge traps compensation

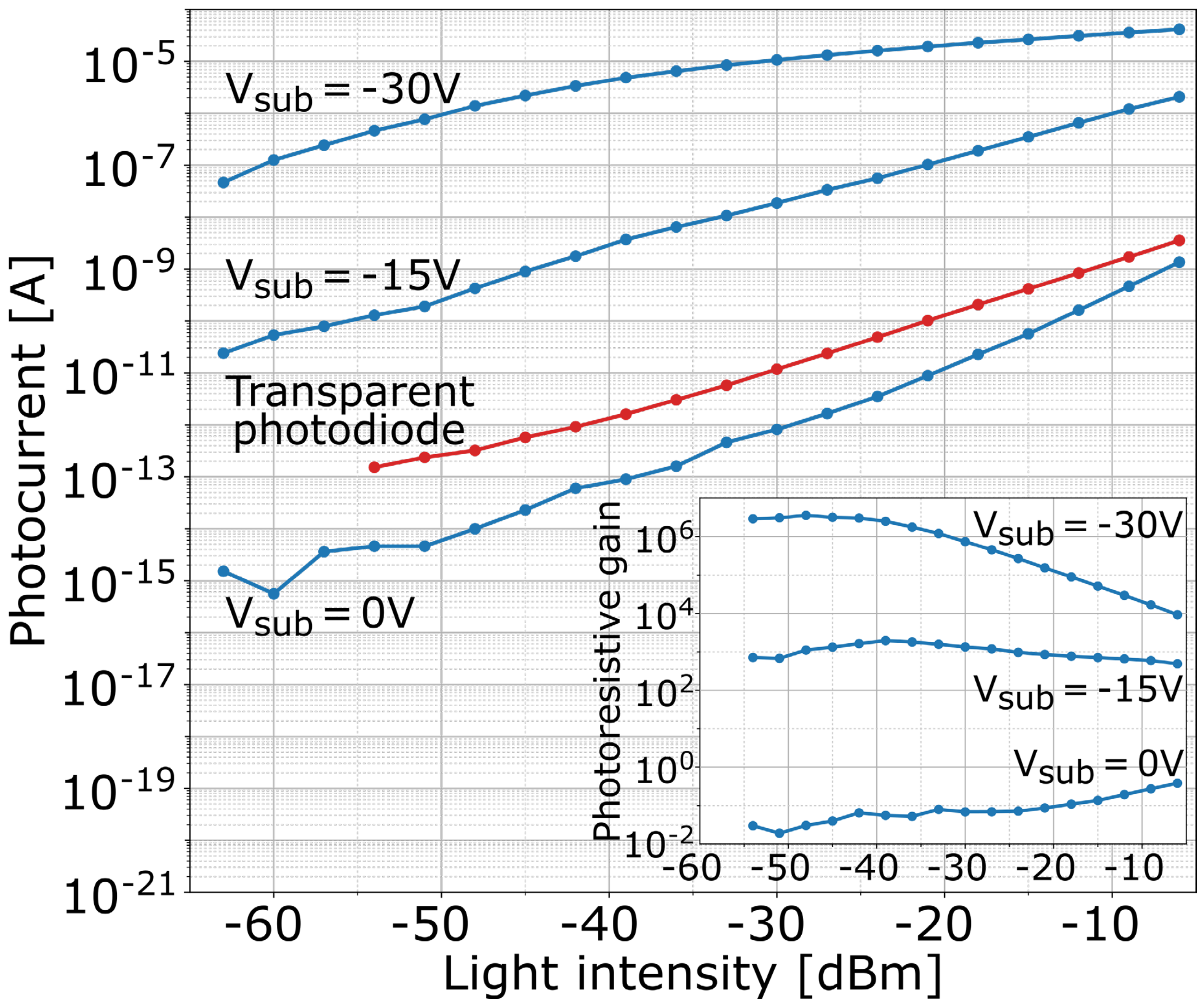
- <u>The detrimental effects of charges and traps on the conduction can be compensated by properly biasing the chip substrate to restore the photoconductive gain!</u>
- The same effect can be obtained by integrating a gate over the WG, to have a more localized compensation action.





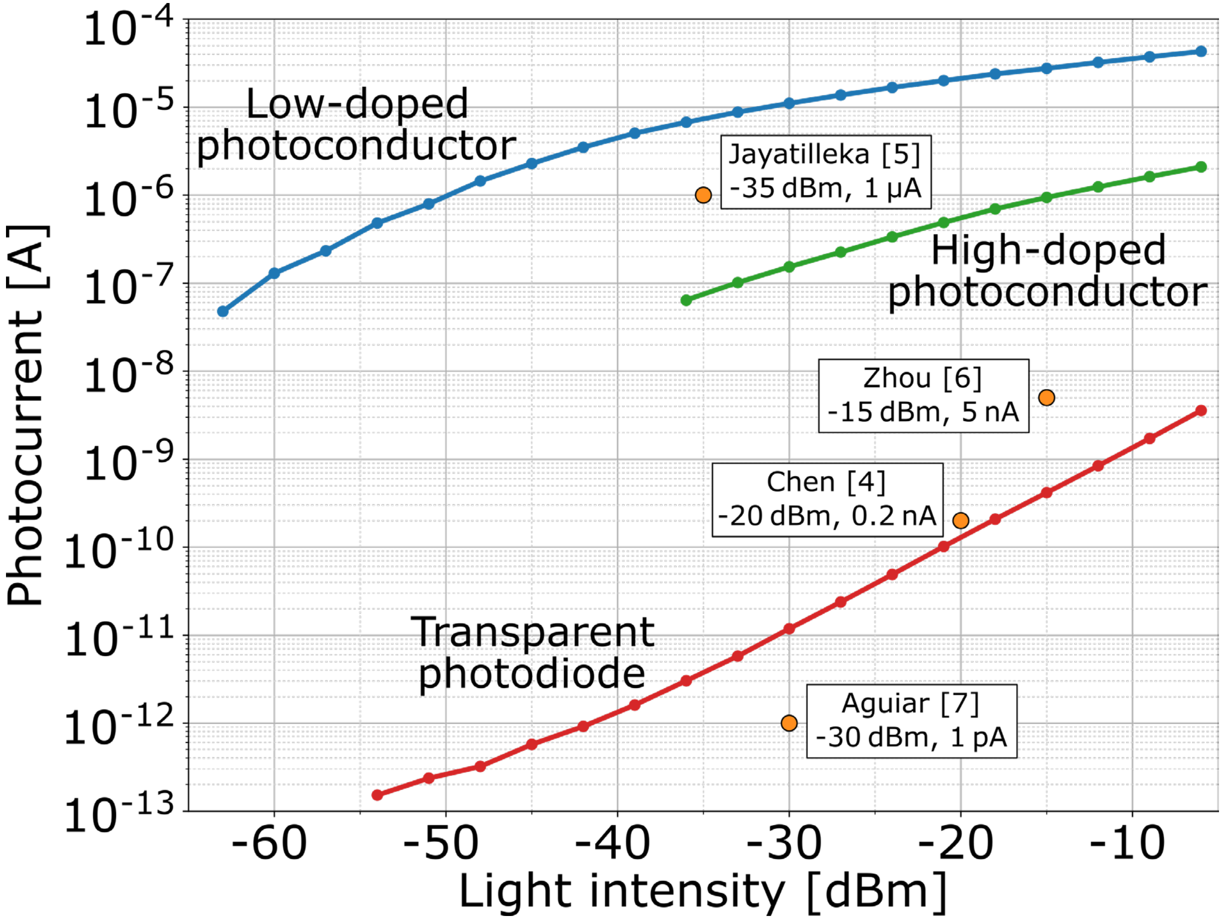
Photoconductive gain vs substrate bias voltage

- By decreasing the substrate bias voltage, the effect of charge traps is completely compensated.
- A high photoconductive gain is observed, since the photogenerated carriers now travel at the expected velocity in the WG.
- The same behavior is not observed in the doped photoconductor, since the high number of native free-carriers makes the effect of charge traps negligible.



Comparison between transparent sensors

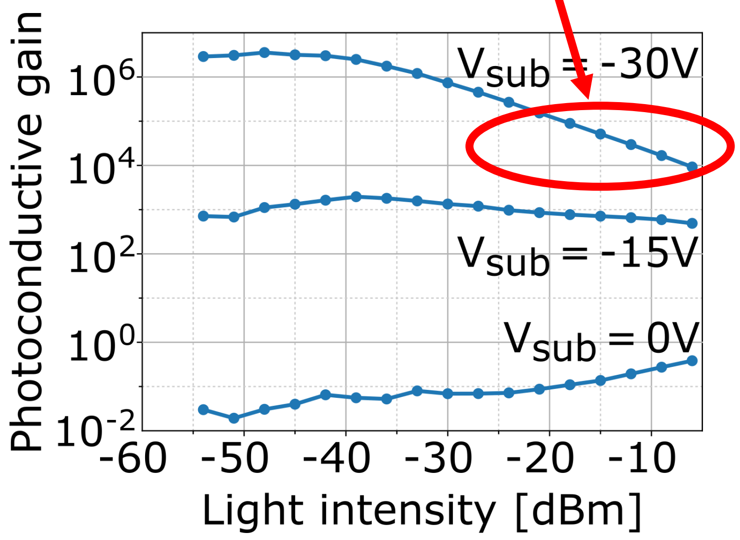
- A correct substrate bias allows to recover the expected device behavior.
- A photoconductive gain of 10^6 is observed, allowing to detect light signals down to -60 dBm.
- As expected, the low-doped photoconductor is more sensitive than the doped one.
- The measurement is performed at low frequency and does not require a custom low-noise electronic readout.

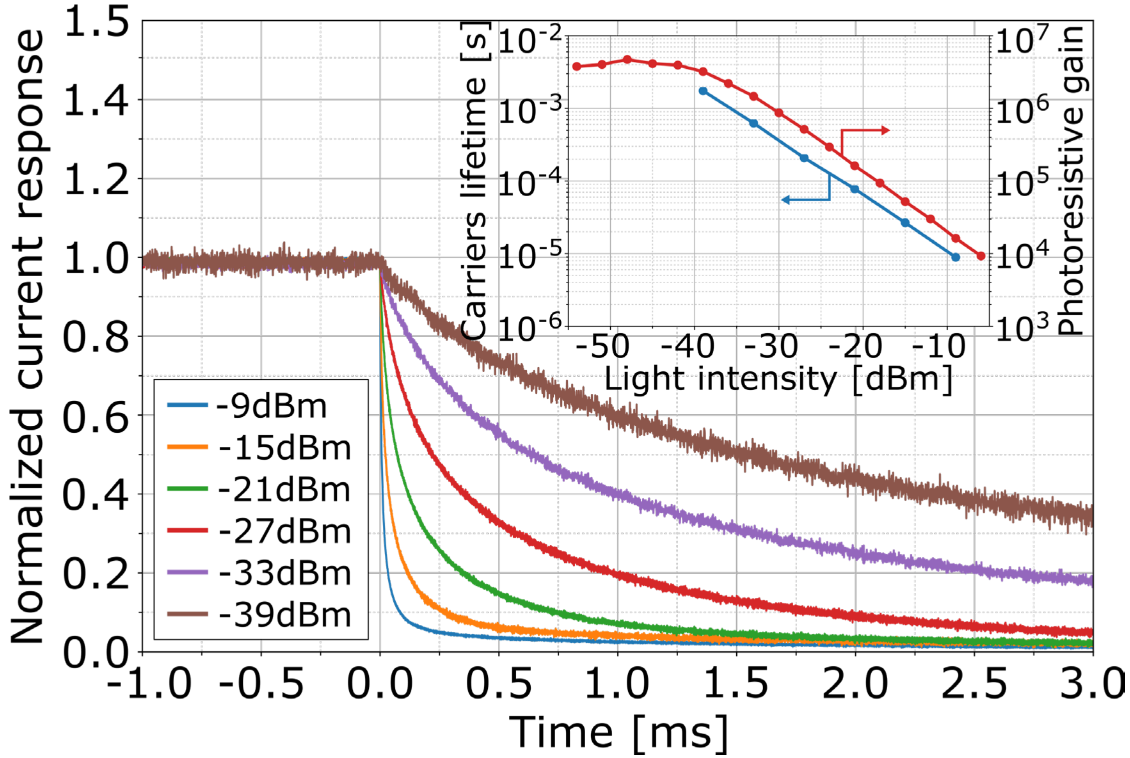


A. Perino et al., Optics Letters, 47, 1327-1330 (2022)

Sensor time response

Why does the photoconductive gain reduce at high light intensity?

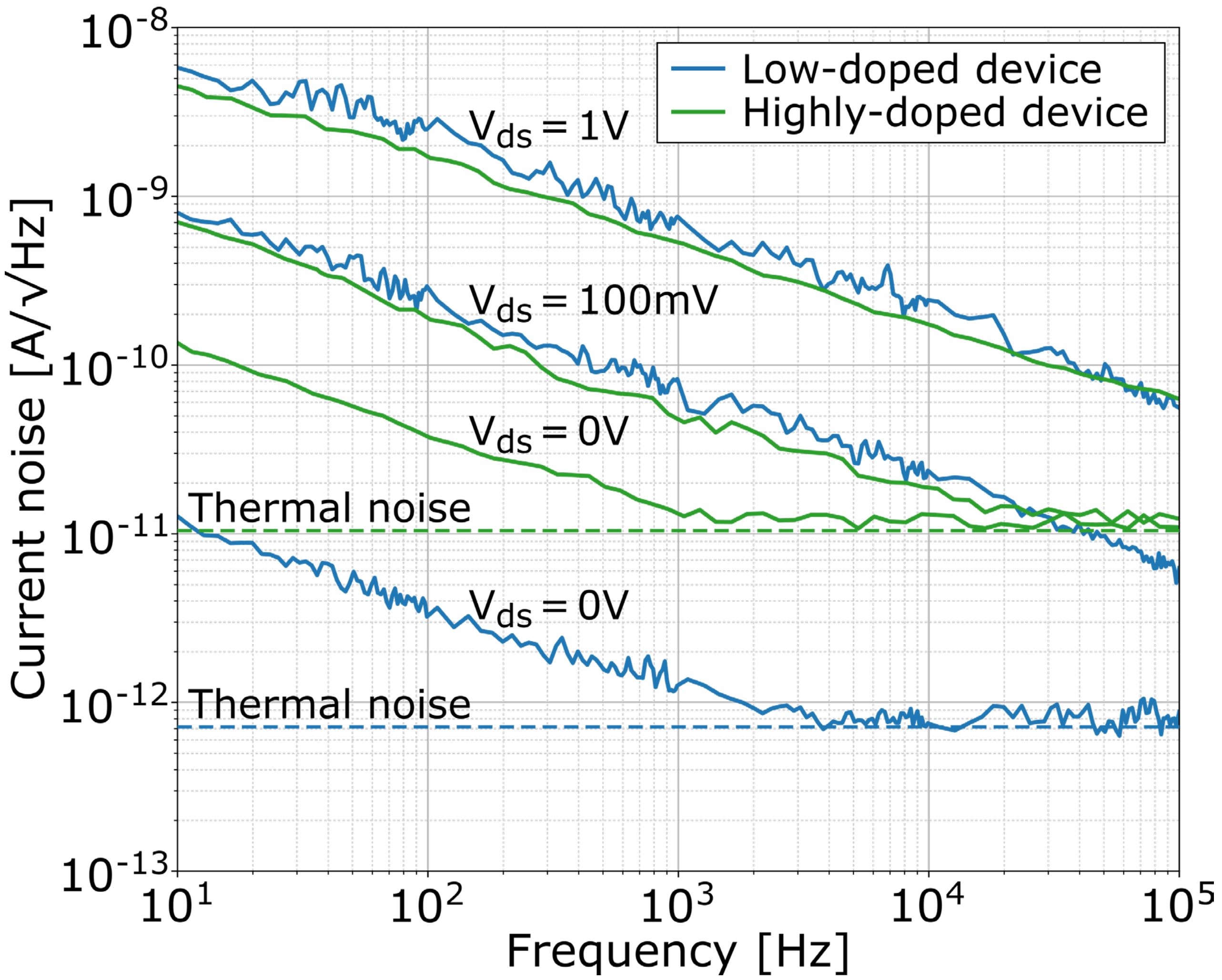




- At high light power, the number of photogenerated free carriers becomes comparable or larger than the native ones due to doping, reducing their lifetime.
- <u>The photoconductive gain increases the detector sensitivity but it limits the readout bandwidth!</u>

Noise behaviour of WG-integrated photoconductors

- The low-doped device has lower thermal noise, due to its higher resistance (i_{NOISE} = 4kT/R)
- An unexpected bias-dependent 1/f noise is observed, with the same level in the two devices.
- The higher sensitivity of the low-doped device is thus only due to its higher photoconductive gain.
- <u>A lock-in readout is beneficial to improve the readout resolution (modulate light, not bias voltage!)</u>



Conclusions

- Transparent light sensors are an important tool in integrated photonics.
- CLIPPs are a good choice in technologies that do not offer the possibility of doping the waveguide, but they require custom readout circuits.
- The photoconductive gain can be exploited to increase the sensitivity of WG-integrated detectors and simplify the readout scheme, at the price of a limited detection bandwidth.