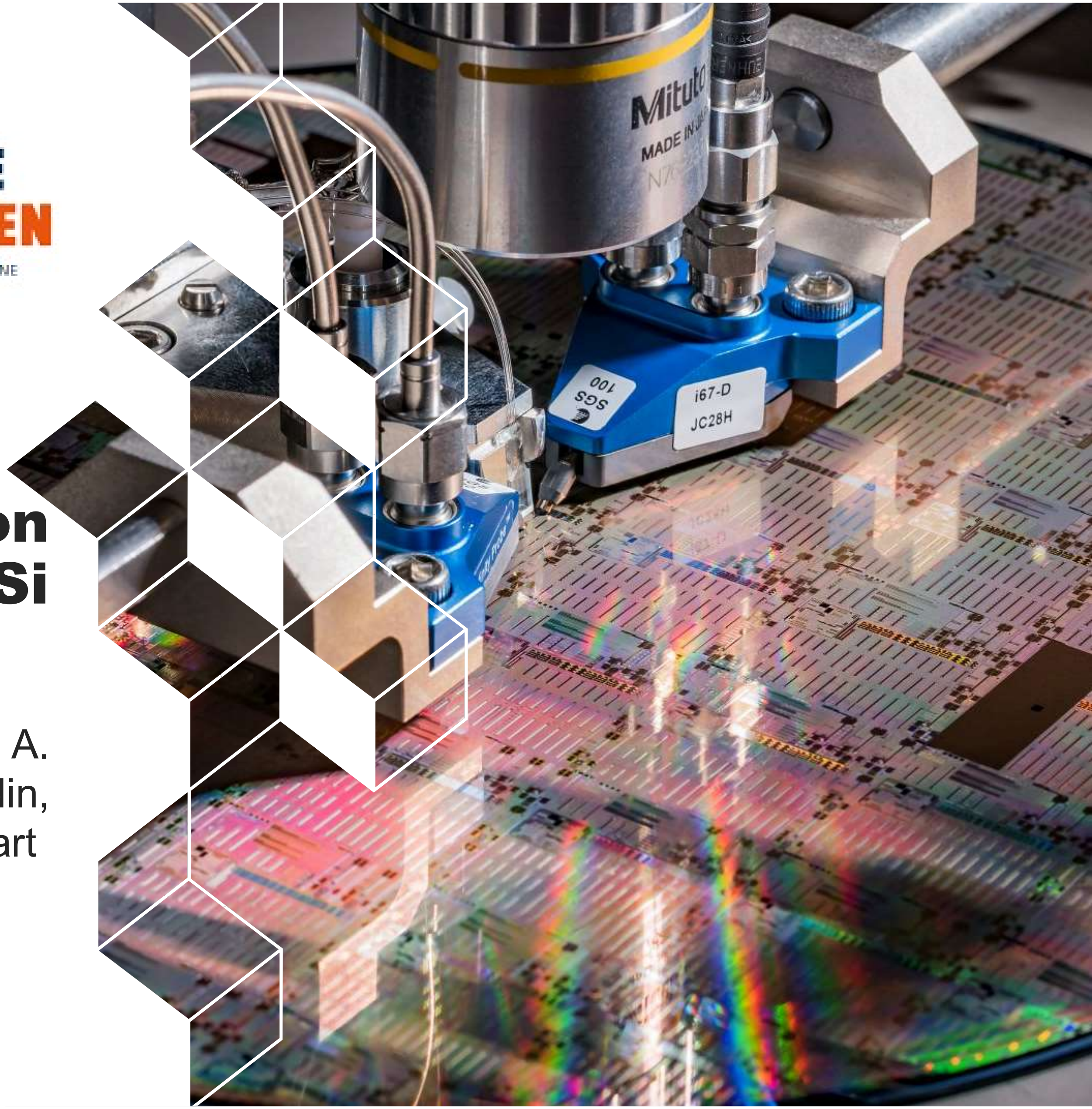
cea

LABORATOIRE HUBERT CURIEN
UMR • CNRS • 5516 • SAINT-ETIENNE

6 MeV electron irradiation effects on integrated Si and SiN-ULL waveguides

I. Reghioua, S. Girard, J. Faugier-Tovar , A. Morana, D. Lambert, P. Grosse, M. Gaillardin, P. Paillet, B. Routier, B. Szelag and Q. Wilmart

RADOPT workshop 2023



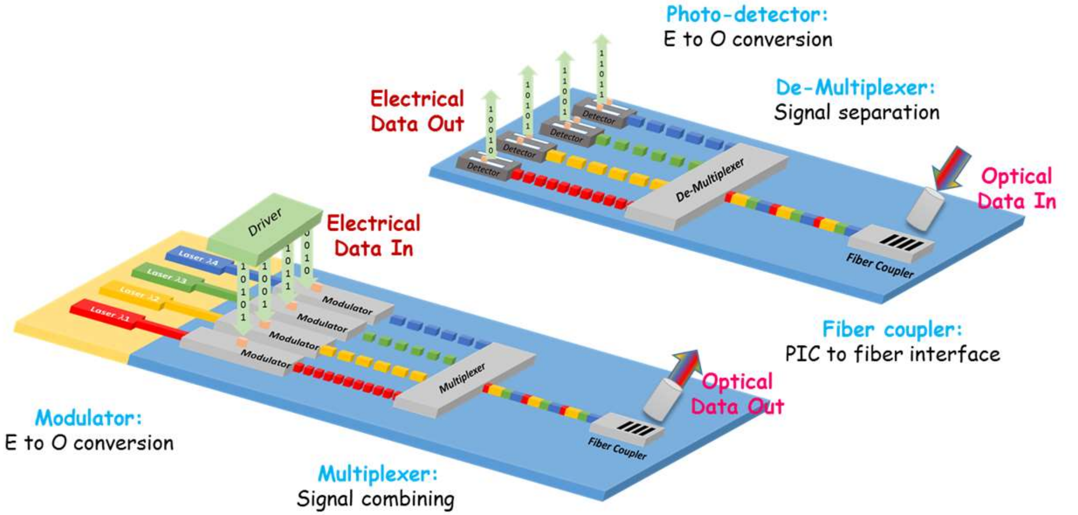
Context

Si-Photonics circuits were historically first used for datacom and telecom applications

- The use of optical fibers has led to increase the speed and capacity of data transmission ➔ the need to develop speed modulators that can directly be connected to the optical fibers (works with light)

- Si-Photonics has allowed to miniaturize the size and enhance the performances of optical components ➔ small foot print, light-weight, lower power consumption and higher reliability.

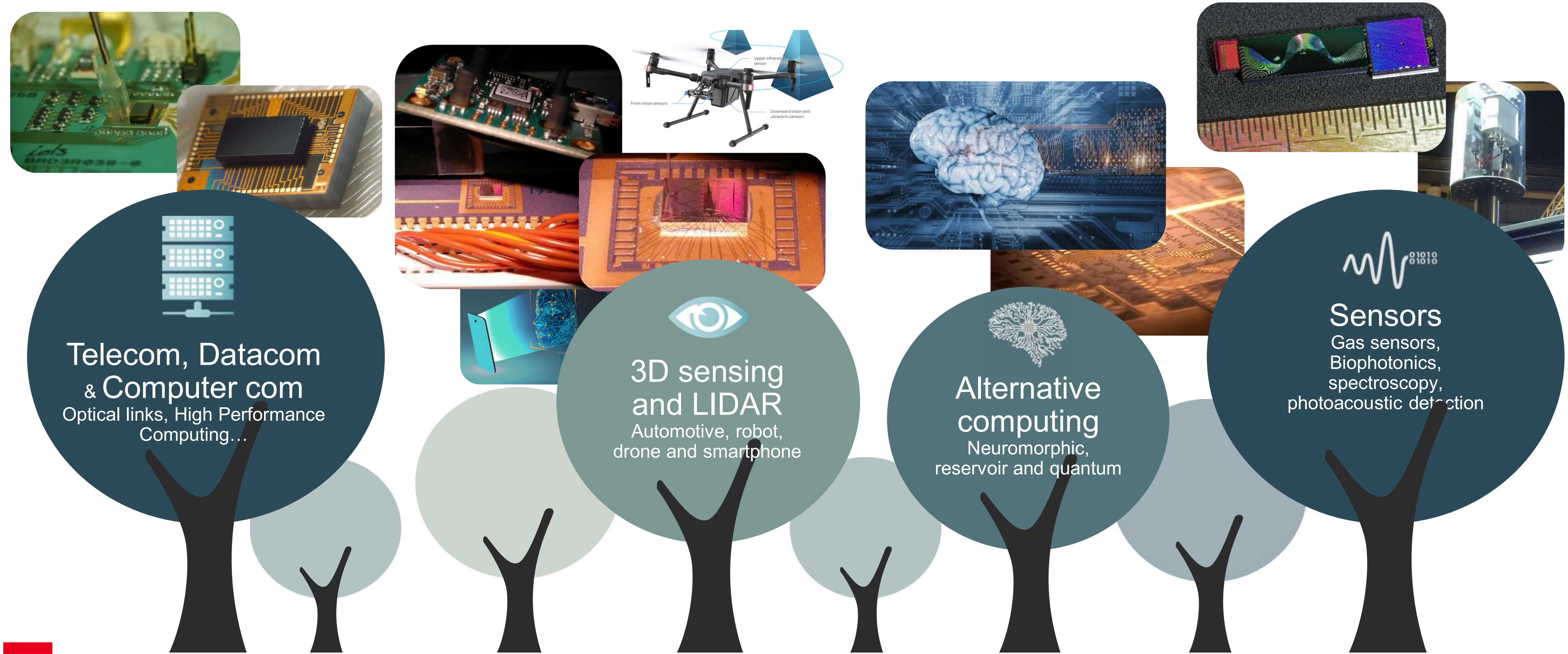
- Si-photonics has the advantage to be compatible with CMOS technology, a mature platform for electronic devices, with some modifications/considerations for photonics.



Si-Photonics Transceiver

Context

Nowadays, Si-Photonics is used for different application fields



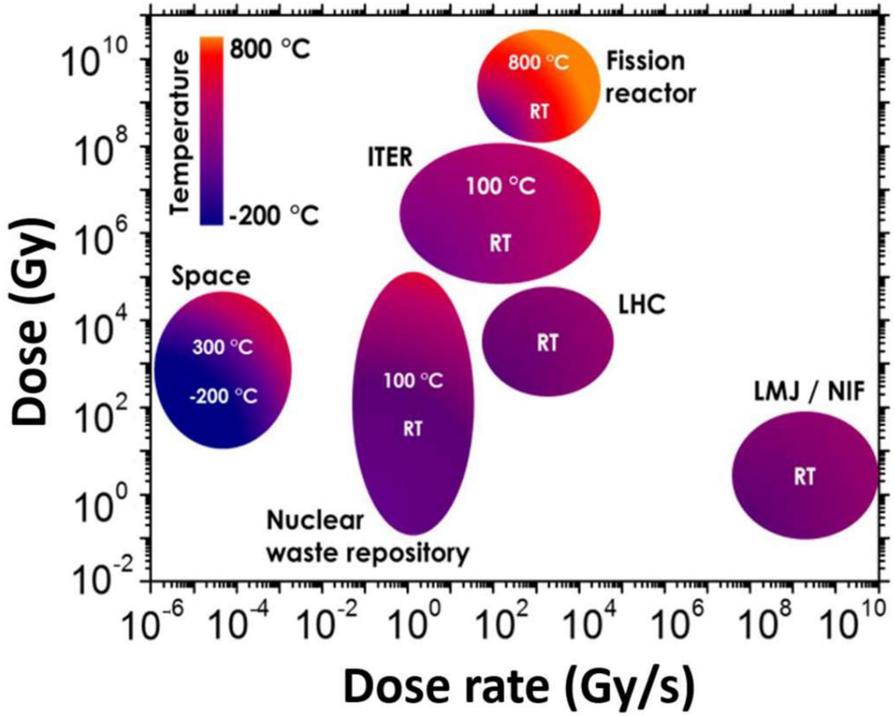
Context

Si-Photonics in Radiation environments

- ❑ Silicon photonic components are high performance and lightweight ➔ promising technology for space and high energy physics applications.

➔Comprehensive studies are required in order to understand the effects of:

- ➢ The Total Ionizing Dose (TID)
- ➢ Displacement Damage (DD)
- ➢ Single Event Transient (SET)
- ➢ Optical Single Event Transient (OSET): An effect that occurs in the optical components within semiconductors

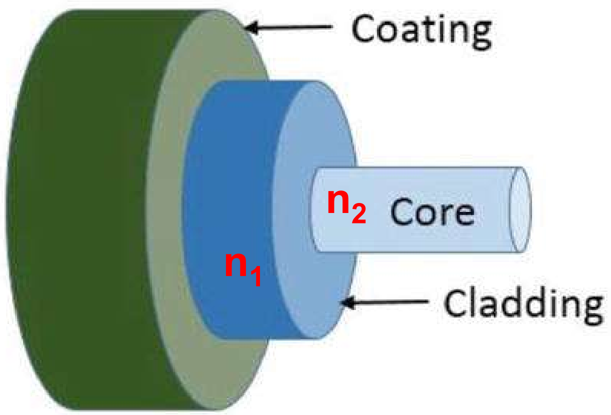


Tzintzarov et al, Photonics, 2021
Tzintzarov et al, TNS, 2021

Si-Photonics waveguides

❑ The basic component in any Si-photonics circuit is the waveguide, but how it works?

Optical fiber



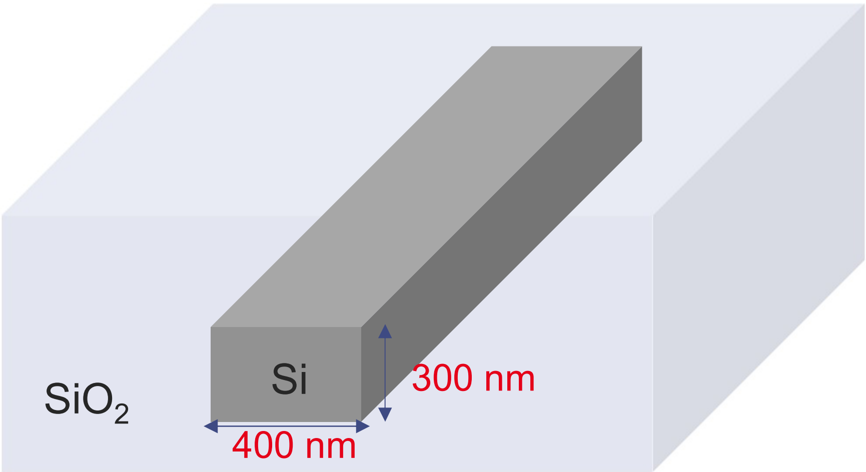
- Optical fibers are usually made of pure silica glass where the refractive index is ~1.45
- For a standard SMF 28, the difference between the refractive index of the core and the one of the cladding is: Δn= ~0.0036
- The core diameter of the optical fiber is 125 µm and the core diameter is ~ 9µm
- The losses are estimated to be: 0.15 dB/km

- $n_{core} > n_{cladding}$ ➔ total internal reflection ➔ light is guided inside the core of the optical fiber

Si-Photonics waveguides

❑ The basic component in any Si-photonics circuit is the waveguide, but how it works?

Silicon waveguide



- The waveguide is made of silicon (n= 3.55) surrounded by silica glass or by air
- For a single mode waveguide, the difference between the refractive index of the core and the one of the cladding is: $\Delta n = \sim 2.1$ (much larger than in optical fibers)
- The core dimensions are 300 nm x 400 nm (much lower than optical fibers)
- The losses are estimated to be: ~ 1 dB/cm for a mRib waveguide (much higher than in optical fibers, but waveguides are integrated in small circuits of few cms)

- $n_{core} >> n_{cladding}$ ➔ small size waveguides, possible integration in a circuit

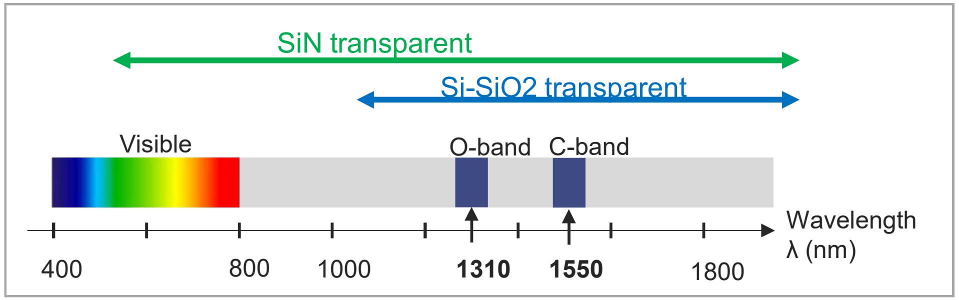
Si-Photonics waveguides

❑ Losses in Si-Waveguides

➢ Absorption

- Transparence of the WG (core and cladding) at the used wavelength➔ bandgap
- Two photon absorption ➔ non-linear effect

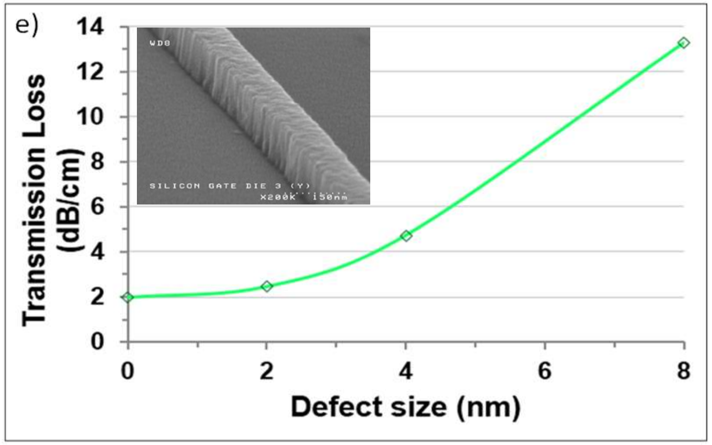
→ Material



➢ Radiation (the amount of light outside the WG)

- Leak of light to the Si substrate (if thin layer of buried oxide BOX)
- Bending losses

→ design



➢ Scattering

Roughness of the waveguide, higher effect whenever the index contrast is higher ➔ the predominant effect for Si waveguides

→ fabrication

Si-waveguides

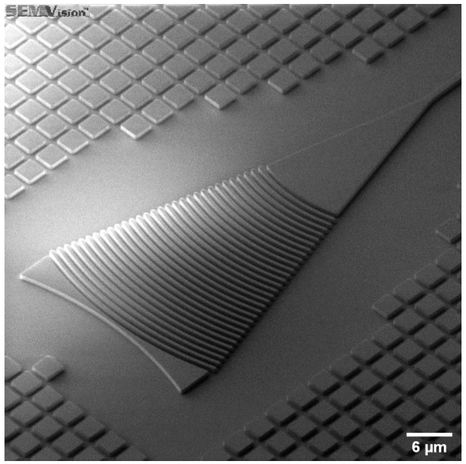
❑ Process integration of Si waveguide (CMOS compatible technology)

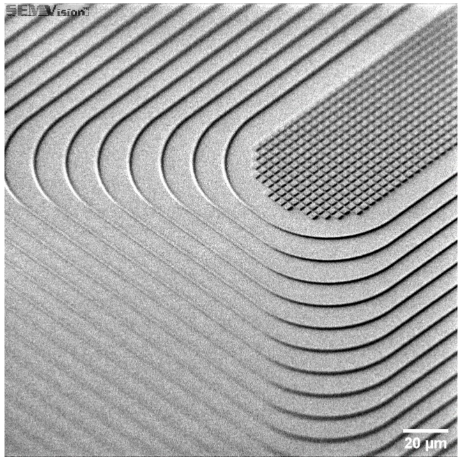
300mm SOI wafer (725µm)

Si patterning (248 nm deep-UV lithography and dry etching)

Silicon oxide cladding

SEM image of a grating coupler





SEM image of spiral of waveguide

SiN-ULL waveguides

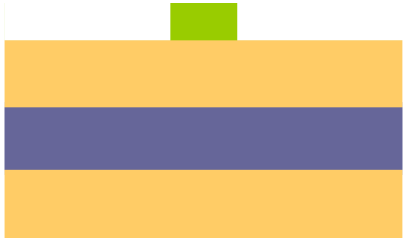
- Silicon nitride has a lower refractive index (~2) ➔ waveguides are larger ➔ lower losses

200mm Silicon wafer (725µm)

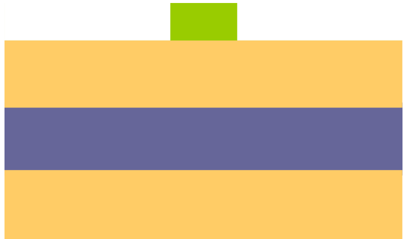
Thermal oxide (3µm)

Deposition of Si_3N_4 film(800nm) by LPCVD*

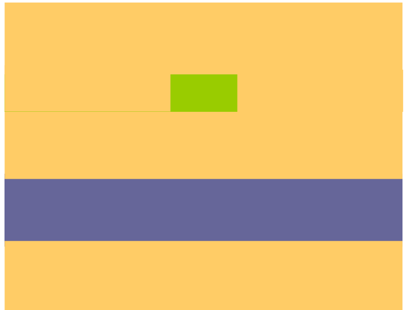
***Low pressure chemical vapor deposition (LPCVD)**



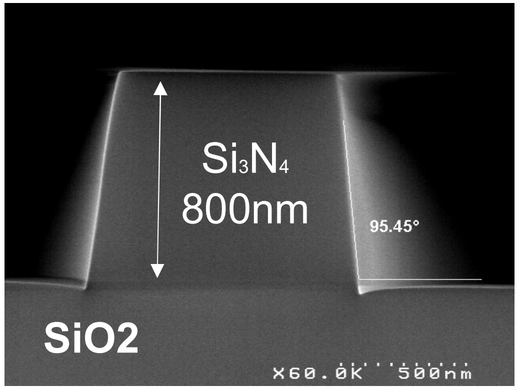
Si_3N_4 patterning (248 nm deep-UV lithography and dry etching)



Annealing of patterned Si_3N_4 waveguides

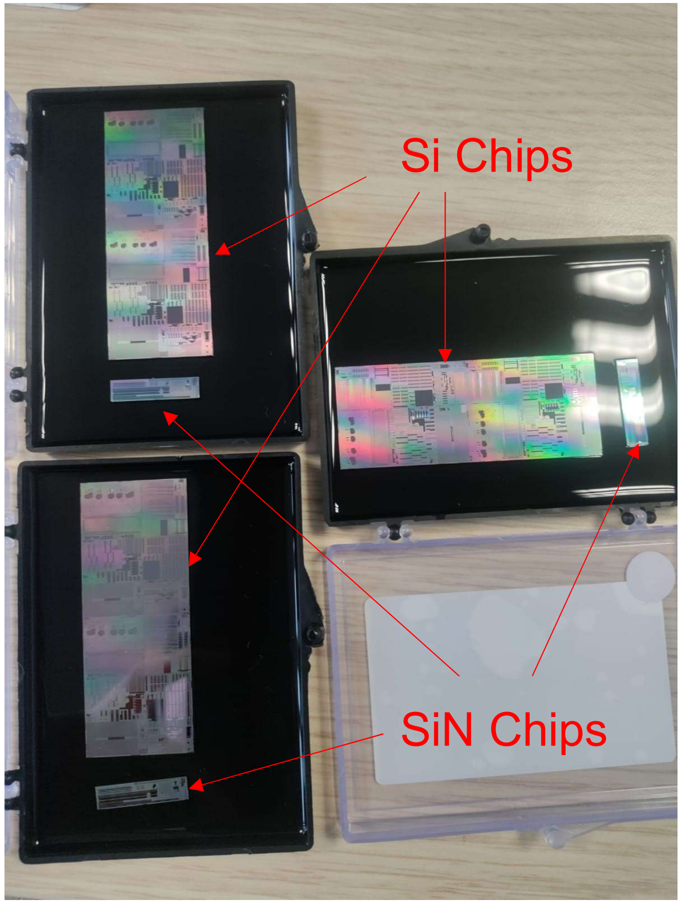


Silicon oxide cladding (2200nm)



H. El-dirani et al, Optics Express, 2019

Electron irradiation



- ❑ The irradiations were performed at ORIATRON electrons facility at CEA-Gramat, France.
- ❑ The electrons have an energy of 6 MeV and a dose rate of 8.44 kGy/min whereas the samples were put at a distance of 1.5 m
- ❑ By varying the exposure time, we obtain the three irradiation doses used for this study: 150 kGy, 1 MGy and 2 MGy.

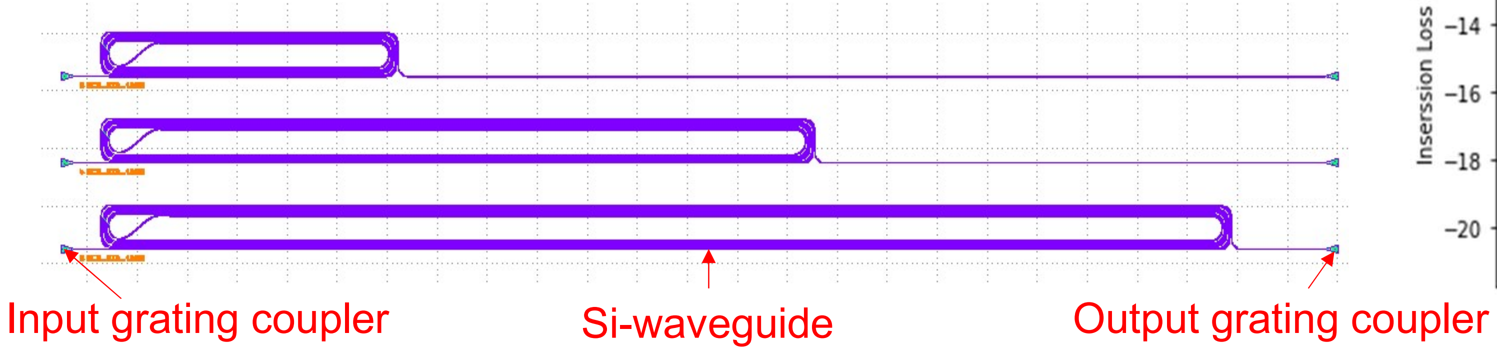
❑ We have irradiated at room temperature:

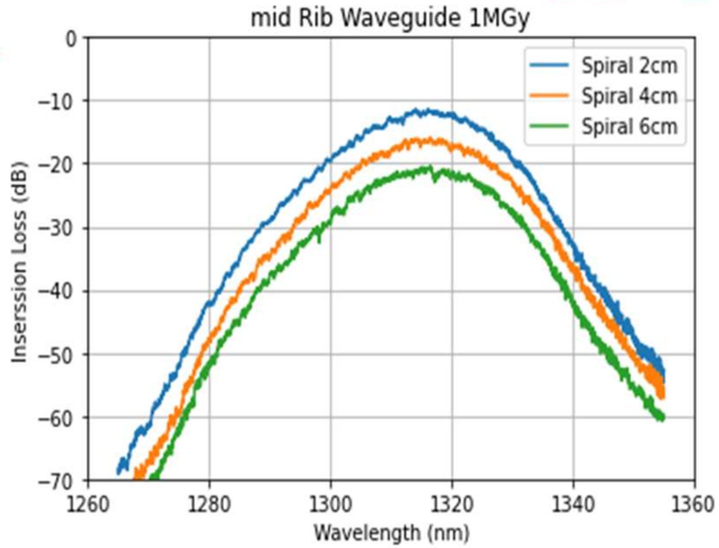
- 3 types of single mode Si-waveguides (Strip, mid Rib and Deep Rib)
- SiN ULL single and multimode waveguides

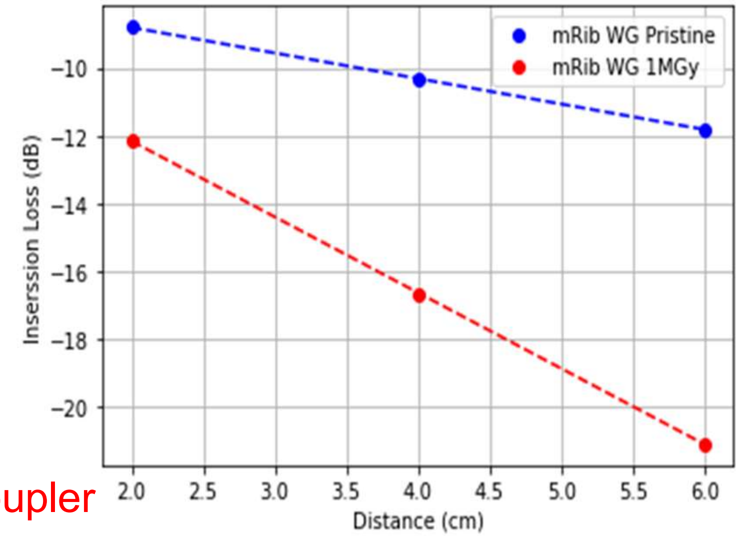
Propagation loss measurements

Cut-Back method:

- Well known in optical fiber loss measurements, it consists of measuring the transmission at different waveguide lengths
- Since there is a linear dependence between the propagation losses and the length of the waveguides, a linear fit is used to extract these losses
- The main advantage of this method is its independence from the coupling losses (related to the coupling in and out of the waveguide through grating couplers)

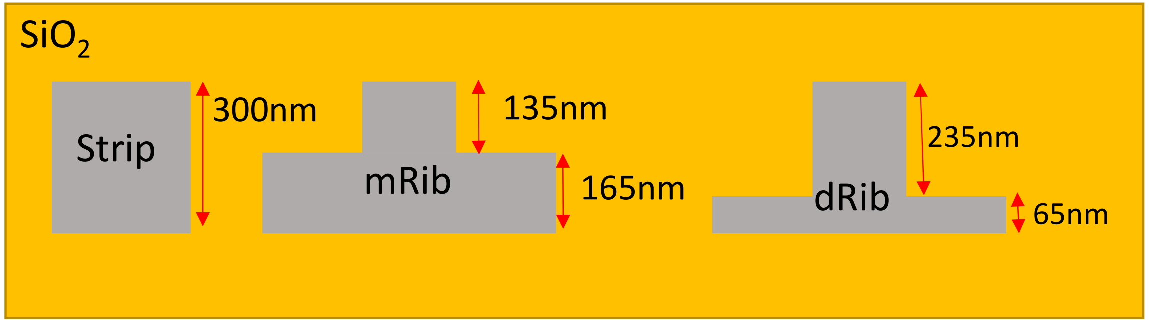




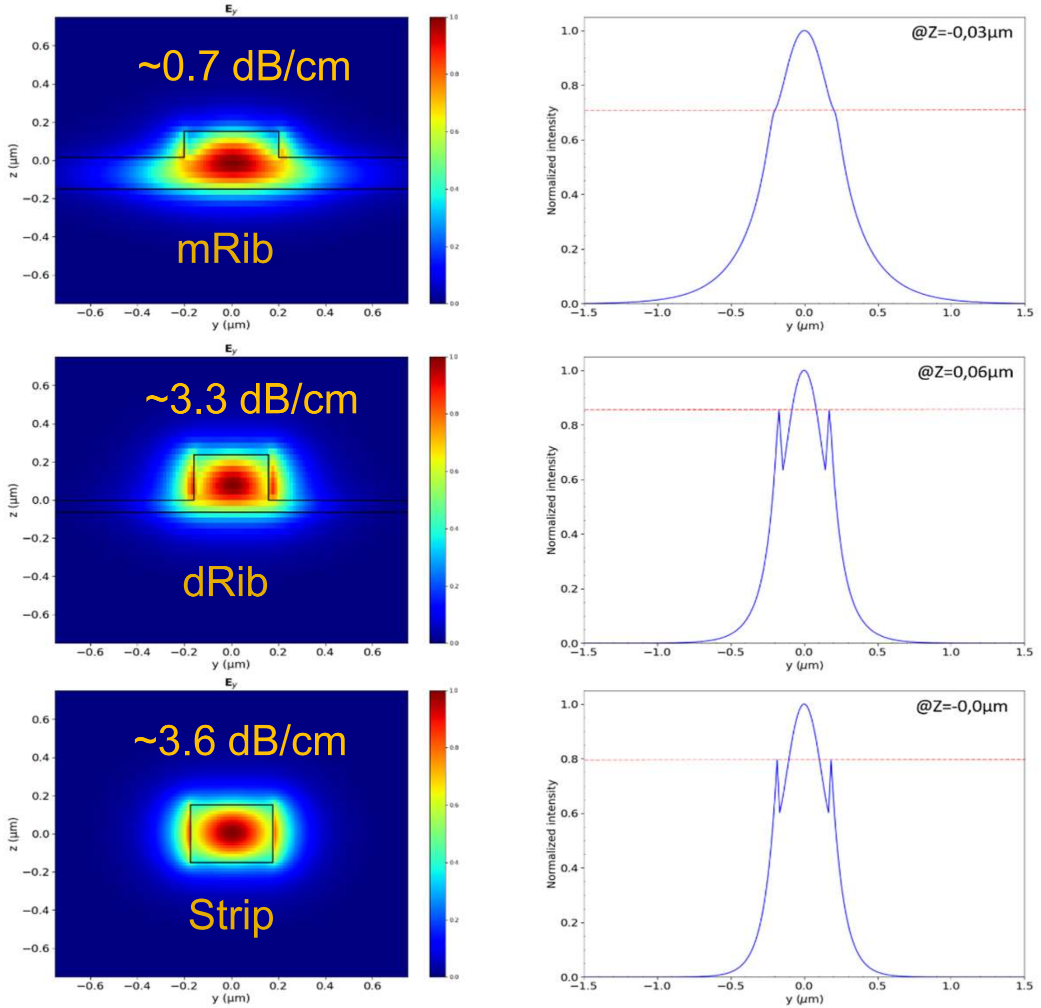


Results

❑ Si-Waveguides before irradiation



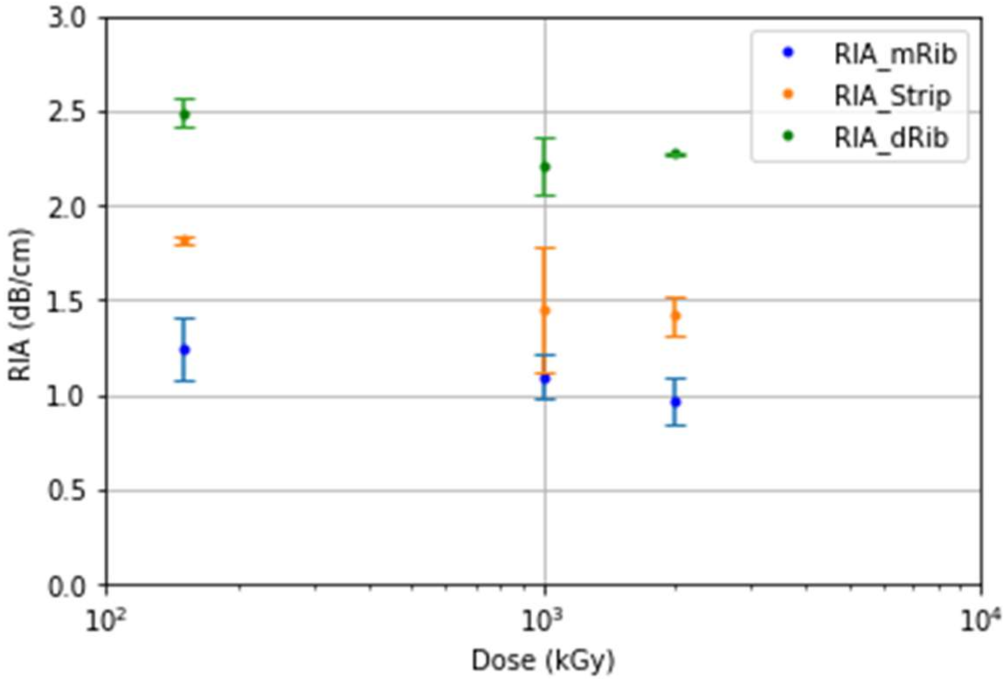
Design	Electrical field intensity at the interface core/clad (%)
Strip	4.23
mRib	1.8
dRib	5.02



Results

❑ Radiation Induced Attenuation (RIA) on Si-waveguides

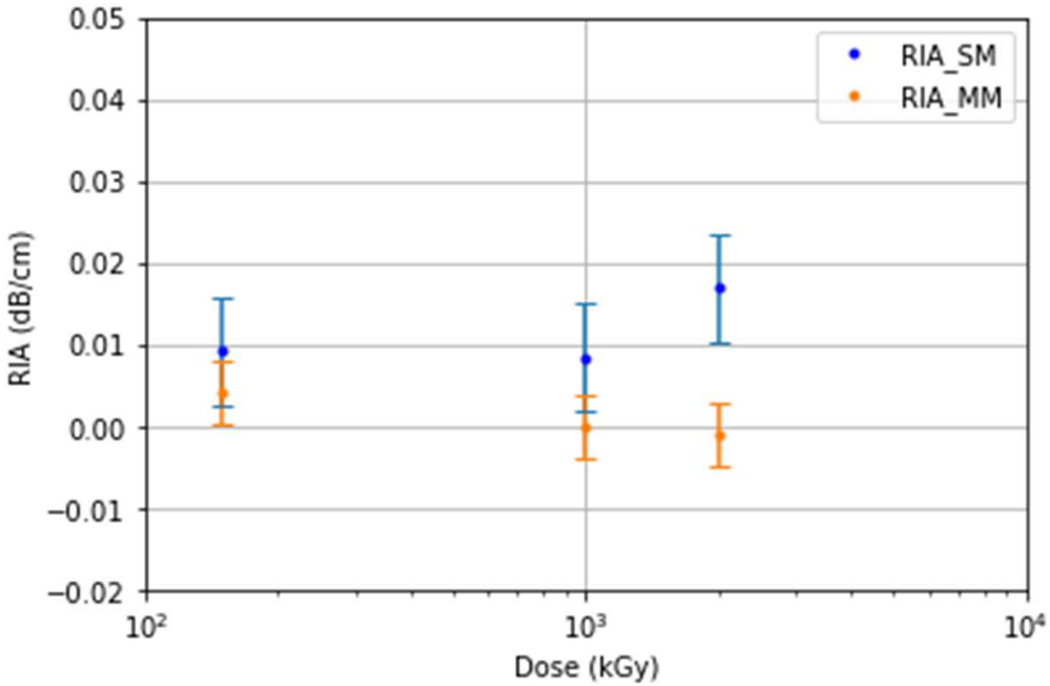
- There is a slight decreasing trend of the RIA as a function of the TID for the three types of waveguides
- The maximum RIA is obtained at the dose of 150 kGy with 1.25, 1.7 and 2.5 dB/cm for the mid-Rib, strip and deep-Rib designs respectively. RIA levels are comparable to those observed after a X-ray irradiation at MGy level (IEEE TNS 2023)
- The mid-Rib design is the most rad-hard design among the three tested against the permanent degradation



Results

❑ Radiation Induced Attenuation (RIA) on SiN-ULL waveguides

- The RIA on both SiN-ULL waveguides (SM and MM) is almost negligible < 0.02 dB/cm
- The maximum RIA is obtained for the SM waveguide at the highest dose (2MGy) with ~0.017 dB/cm where the RIA on the MM waveguides is around zero at this dose
- Before irradiation, the SM waveguides (900 nm width) have ~0.13 dB/cm of propagation loss whereas the MM ones (1700 nm width) have 0.05 dB/cm.



Conclusion and perspectives

- The permanent RIA on Si-waveguides has shown to be at its maximum at 150 kGy of 6MeV electron irradiation (among the tested TID), and then it exhibits a slight decrease for the three waveguide types, which can be explained by a recovery process
- The mRib design has shown its better tolerance towards TID (same results were reported on X-rays irradiation), which can be explained by the lower interaction of the guided mode with the core/clad interface in this architecture of waveguides
- The SiN-ULL waveguides have shown no significant RIA up to the MGy level, which indicates that the SiN-ULL waveguides are rad-hard to permanent damages caused by high TID electron exposures and can be considered as promising candidate for applications in electron-rich environments
- The fact that SiN-ULL MM waveguides have shown even a better tolerance with an RIA around zero, can also be explained by its larger width, and hence the lower overlap between the guided mode and the core/clad interface. This interface contains defects and traps where the transmitted optical signal can be degraded.
- Further in-situ measurements are needed in order to follow the transient effects and better understand the basic mechanisms responsible for any potential degradation

Thank you for your attention

Prénom NOM (premier niveau)
Prenom.nom@cea.fr (deuxième niveau)
06 00 00 00 00 (deuxième niveau)

Matériaux : couleur et code RVB Windows associés

Ag (192/192/192)	**COFex** **(255/153/153)**	**HfZr** **(0/51/102)**	**Pt, PtSi** **(102/0/102)**	**Sn** (221/221/221)
Al, AlCu, AlSi (51/153/255)	**Cr** (102/102/51)	**HTO** (255/204/204)	**PZT,LNO,LTO** (0/102/102)	**STO** (0/128/128)
Al2O3 102/153/255)	**Cu** (255/102/0)	**IrMnx** (0/102/153)	**Rés. >0** (255/0/102)	**Ta, Ta2O5, TaN** (51/51/0)
AlGaInP, InP (51/204/204)	**FeNi** (204/204/0)	**ITO** (204/153/0)	**Rés. <0** (153/0/204)	**Te** (153/51/102)
AlN (204/153/255)	**InGaAs, GaAs, GaN** (204/102/0)	**LiCo, LiPON** (0/102/102)	**Ru** (0/255/0)	**Ti** (0/102/255)
AlTi 204/204/255)	**GaSb** (205/204/0)	**Mo** (119/119/119)	**Si** (102/102/153)	**TiN** (204/51/0)
Au (255/255/0)	**Ge** (102/255/102)	**Nb** (0/152/0)	**aSi ou pSi** (255/0/0)	**TiO2** (255/204/153)
B (153/102/0)	**GeS** (102/255/204)	**Ni** (204/51/204)	**SiC, SiCN** (102/0/204)	**TiW** (0/102/0)
Bi (51/51/204)	**GeSe** (150/150/150)	**NiFex** (204/0/102)	**SiGe** (51/102/0)	**Verre (substrat)** (153/255/204)
BST (255/255/255)	**GeTe** (178/178/178)	**NiO** (165/0/33)	**SiO2** (255/204/102)	**W** (255/0/102)
C (153/153/255)	**GST** (0/51/0)	**NiSi** (0/0/0)	**SiON** (102/255/153)	
CO (0/0/204)	**Hf02** (205/153/51)	**Polyimide** (102/0/51)	**SiN** (153/204/0)	