Holistic approach for VCSEL wavelength selection

Rubén Pérez-Aranda, KDPOF

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Supporters

- Joseph Pankert, TRUMPF
- Roger King, TRUMPF

Introduction

- Several contributions have already shown that wavelength is a fundamental parameter that impacts in the VCSEL reliability as well as in the PHY complexity
- However, there are other parameters that should be considered in order to do an educated wavelength choice optimum for automotive applications
- In this contribution, parameters as the following ones, will be analyzed as inputs for the wavelength selection:
  - VCSEL Reliability
  - Fiber characteristics
  - Photodiode (PD) material and responsivity
  - ICs assembly options
- A final summary will be given intended to help for an educated wavelength choice

VCSEL reliability

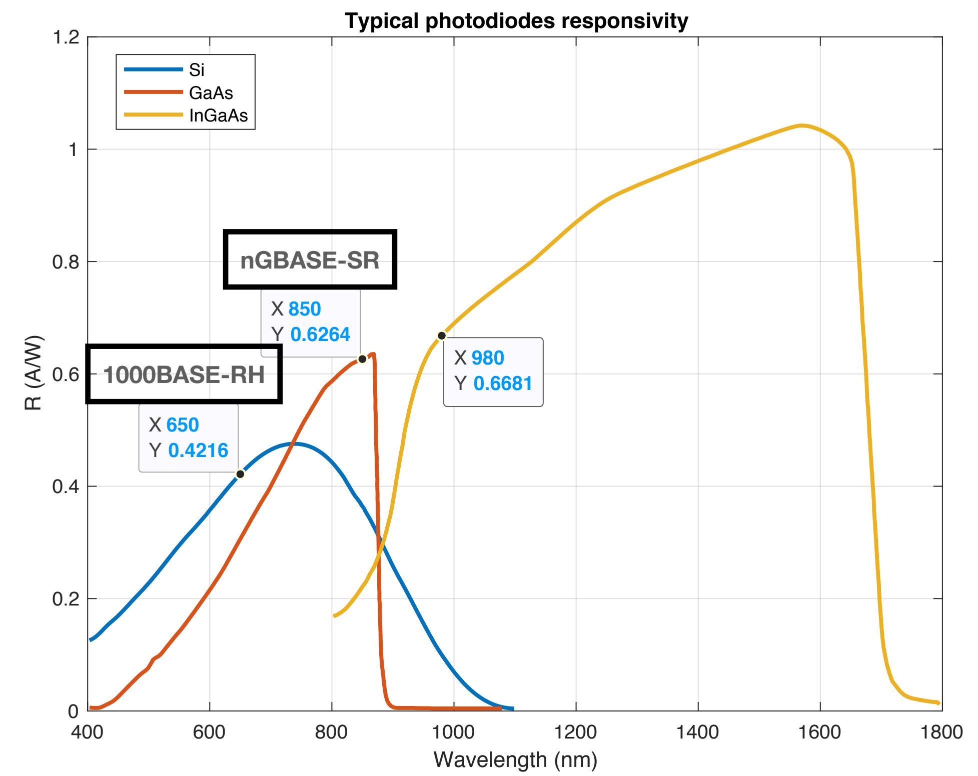
- Wear-out reliability: going for 850nm may be possible, but coming with several penalties compared with 980nm VCSEL
  - Driving current reduction is required [3, 4, 5]
  - Reduced speed and signal integrity [6, 7]
  - Increased transceiver complexity and power consumption (TX FFE, RX EQ, ADC) [6, 7]
  - More difficult VCSEL design, smaller number of players in the market [1]
- Wear-out reliability: going for 980nm is a much safer bet and not hampered by compatibility issues [1]
  - 980nm VCSELs are far more robust than 850nm VCSELs
  - Automotive is not requiring backwards compatibility
  - Plenty of suppliers capable of delivering robust 980nm VCSELs,
- Multi-vendor availability [1]
  - Reliable QWs are much easier to produce in 940 and 980 nm
  - Epitaxial alchemy is the biggest hurdle at 850 nm (most VCSEL suppliers fail)
- The game-changer for improved wear out reliability is the use of aluminum-free quantum well barriers [1]
  - 940nm and 980nm are equally reliable
  - 940nm will be considered in the analysis of other parameters too
- Random failures [2]
  - Very high knowledge by industry, specially due to the very high volume production of 940nm VCSELs in smart phone applications and using similar current density as datacom 850nm
  - The key is the use of low-defect substrates
  - Substrates for 850nm, 940nm, 980nm are identical, so no influence in wavelength choice

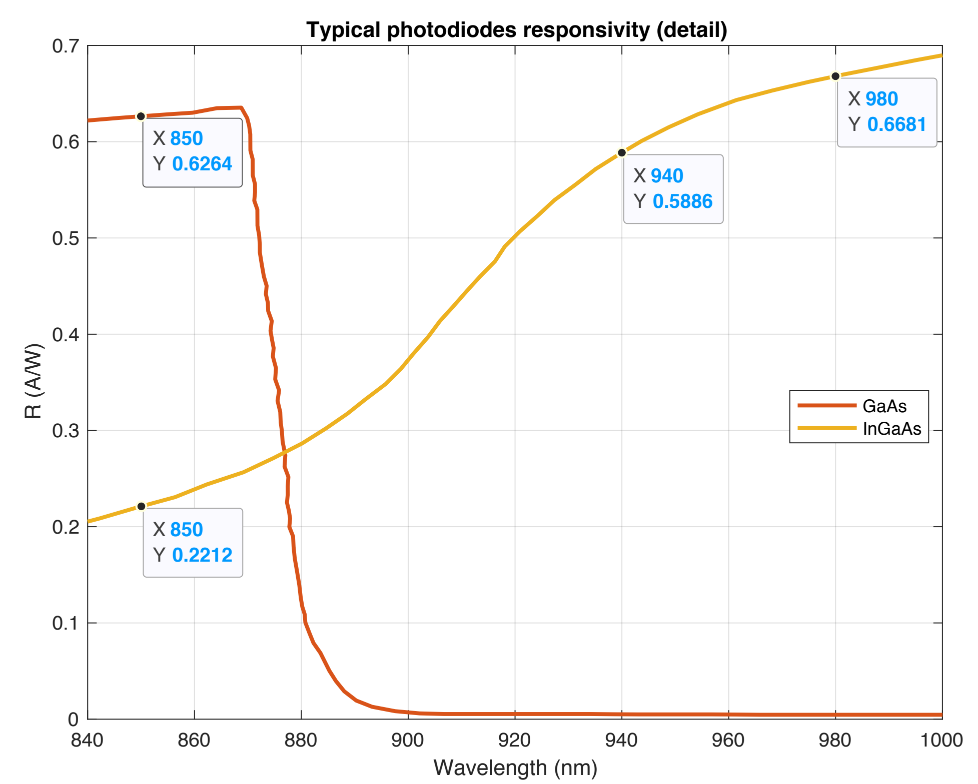
OM3 fiber characteristics

- Chromatic dispersion decreases with longer wavelengths, however the effective bandwidth-length product of OM3 fiber is fundamentally limited by modal dispersion per EMBc method
- The IEC guidance [11] developed extends from 840nm to 953nm as a consensus worst-case estimate in TIA [12]
- Despite 980nm is not included in such IEC guidance, EMB has been agreed among individuals affiliated with Corning, Panduit and KDPOF, to be ~950 MHz·km at 980nm [8, 9, 10]
  - BW_{eff} = 936 MHz·km, considering BW_{CD} = 5498 MHz·km @ 980nm
- 40 meters is the max link length considered in the project's objectives
- In [10] the effect of reduced 980nm EMB vs 850nm in the RX sensitivity was reported to be less than 0.25 dB for all the characterized VCSELs in 125ºC, 25 Gb/s and 40 meters OM3
  - In [13] the effect of reduced 980nm EMB vs 850nm was reported to be < 0.3 dB for 50 Gb/s, 40m, 125C
- As conclusion, OM3 fiber characteristics are not determinant for the wavelength selection

Photodiode responsivity

- Disclaimer: only mature and widely available photodiodes are analyzed in this section
  - Maturity: large knowhow in fabrication, characteristics, reliability
  - Availability: automotive is a cost driven application
- Photodiodes:
  - They are semiconductor devices responsive to photons
  - They operate by absorption of photons and generate a flow of electrical current (A) in an external circuit, proportional to the incident optical power (W)
- Responsivity (A/W) depends on the material and the wavelength, being different materials optimal for different wavelength ranges
  - The band gap energies of the materials produce different cutoff wavelengths of photodiodes
- High absorption is also important to get high speed photo-current conversion by allowing thin absorption layers operating with low reverse voltage biasing
- Si PDs are used in 1000BASE-RH (GEPOF) systems operating at 650nm
- GaAs PDs are commonly used for 850nm systems (e.g. nGBASE-SR)
- InGaAs PDs are commonly used in longer wavelengths (e.g. 1300 and 1550 nm systems) as well as in many lab equipment, and it can be used at 940nm and 980nm
- InGaAs PDs are grown over InP (lattice matching)



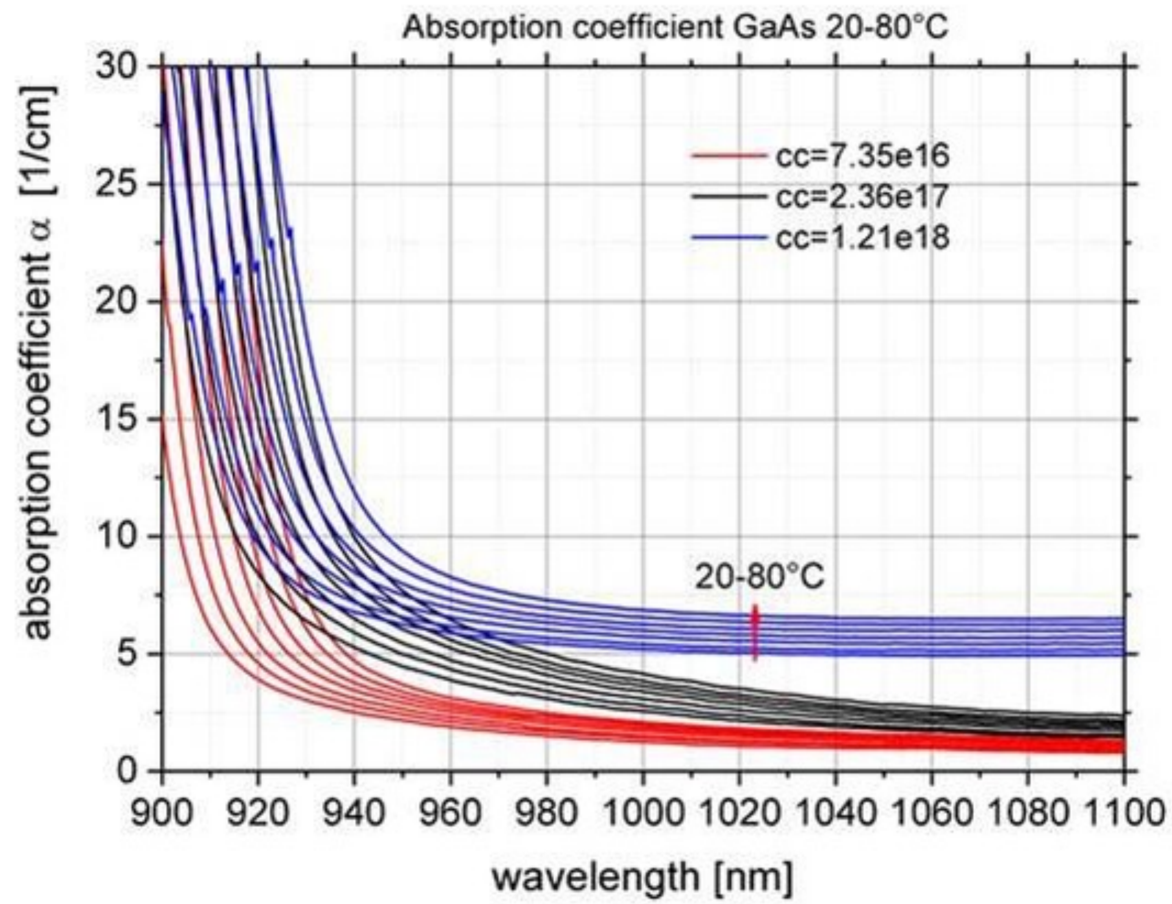


Assembly, flip-chip option

- IC assembly is an implementation matter (vs. interoperability). However, it needs to be taken into account in the wavelength selection in order to avoid precluding implementation options that are advantageous for the targeted application
- Flip-chip assembly presents several advantages over die / wire bonding for the targeted application that makes it a recommended option
  - Better **positioning** accuracy: good for lid and optics to photonics alignment
  - Better photonics ICs **tilt control**: specially important in case of using EBO (Expanded Beam Optics) in the PHY optical interface
  - Better **signal integrity**: not really needed for rates ≤ 10 Gb/s, but it is advantageous for rates ≥ 25 Gb/s
  - Much **higher production throughput** with good accuracy
  - Much **lower cost**, specially because the reduced assembly cycle time with demanded positioning accuracy
  - Flip-chip **bumps** addition process is very cheap and automotive qualified in the main foundries
  - Flip-chip is already **automotive qualified** in the main **packaging** companies
- In order to be able to assembly VCSEL and PD using flip-chip process it is required:
  - Bottom emission of the VCSEL
  - Bottom illumination of the PD
- Substrate light absorption (transmittance inverse) has a big dependency with the material and the wavelength

Assembly, flip-chip option: VCSEL

- VCSELs are grown over GaAs substrate, so this substrate will absorb part of the emitted light in a bottom emission device
- In general, the GaAs absorption:
  - increases with temperature
  - decreases with wavelength
- Longer wavelengths experience much lower absorption, hence better transmittance
- Let's consider cc = 7.35e16, 80ºC, and 200 um substrate thickness:
  - **980nm:** α = 3 cm^{-1}, att = 5.8%, **IL = 0.26 dB**
  - **940nm:** α = 5 cm^{-1}, att = 9.5%, **IL = 0.43 dB**
  - **910nm:** α > 30 cm^{-1}, att > 45%, **IL > 2.6 dB**
  - **850nm: att ~100%**, GaAs is the material used to absorb photons in 850nm photodiodes!
- 980 nm is the best choice: lowest absorption, less process dependency because it is after the curve elbow
- 940 nm is feasible but just in the elbow, so more sensible to process variations
- 850 nm is not feasible for bottom emission devices

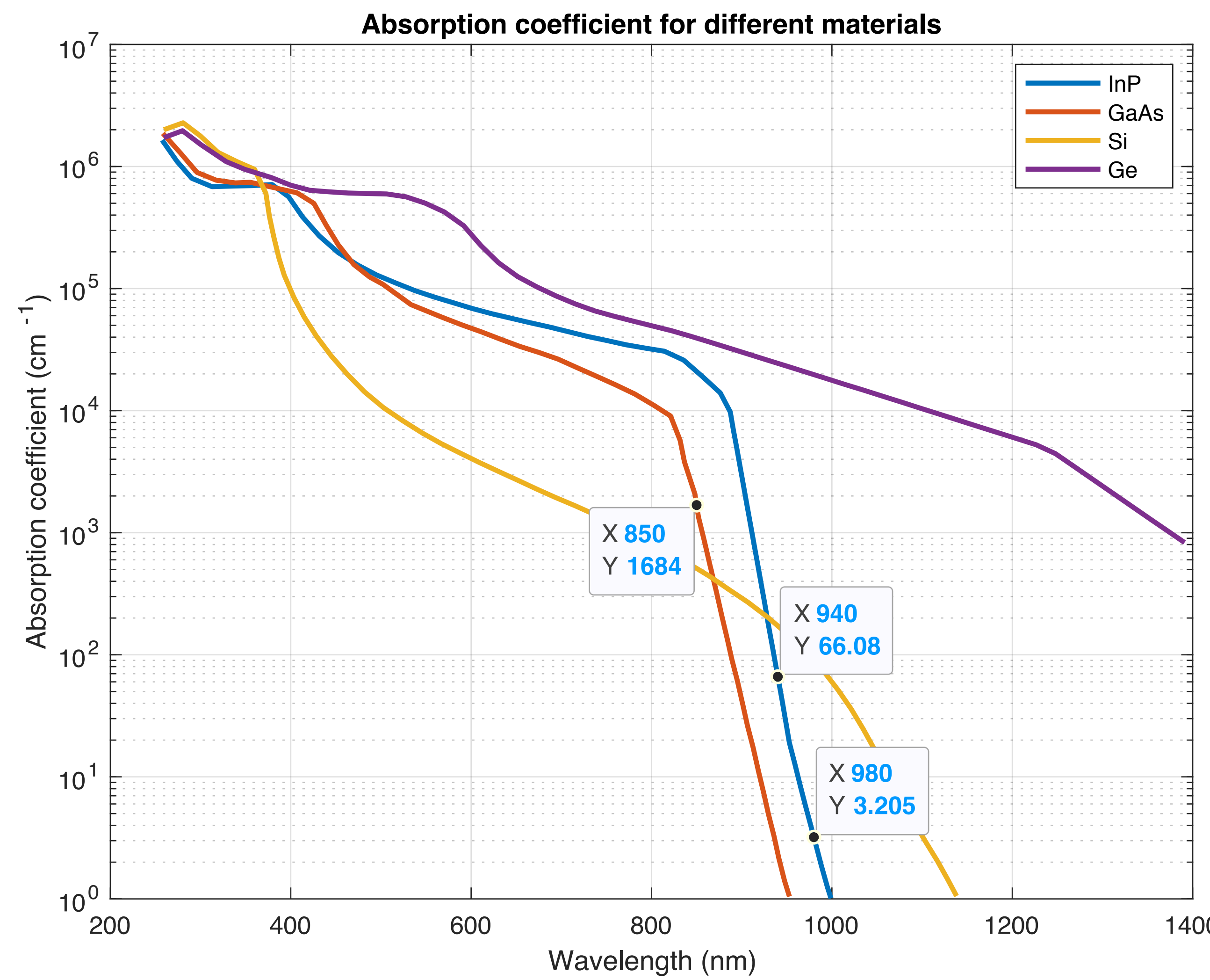


GaAs absorption coefficient as a function of dopant concentration (cubic centimeters), temperature and wavelength

Different colors indicate different dopant concentrations

Assembly, flip-chip option: PD

- From the VCSEL point of view 850nm is not a valid wavelength for bottom emission
- Therefore, in this section we only analyze 940 nm and 980 nm regarding bottom illumination PD devices
- InGaAs PDs are grown over InP substrate (lattice matching)
- In order to discriminate between 940 nm and 980 nm, InP absorption is calculated for both wavelengths
- Let's assume 200 um substrate thickness:
  - 980nm: α = 3.2 cm^{-1}, att = 6.2%, **IL = 0.28 dB**
    - net R_{PD} = 0.67 · 0.94 = 0.63 A/W,
    - **consistent with link budget analysis, i.e. 0.6 A/W**
  - 940nm: α = 66 cm^{-1}, att = 73%, **IL = 5.73 dB**
    - net R_{PD} = 0.67 · 0.27 = 0.18 A/W,
    - **5.5 dB penalty wrt 980 nm**



Conclusions

	Wavelength (nm)		
Criteria	**850**	**940**	**980**
VCSEL wear-out reliability	Limited, current density needs to be under control in high temperature	Very good	Very good
VCSEL random failures reliability	No difference. Very good with low defect substrates		
VCSEL multi-vendor availability	Most of VCSEL suppliers fail	Reliable & high speed VCSELs are much easier to produce	
PHY complexity, TX FFE	Needed to compensate lower VCSEL bandwidth and AOP	Not needed	Not needed
PHY complexity, RX ADC + EQ	Higher complexity to compensate lower VCSEL bandwidth and AOP	Less complex	Less complex
OM3 fiber	No relevant difference. RX sensitivity loss due to reduced EMB is less than 0.3 dB at 40 meters at 50 Gb/s.		
Photodiode material	GaAs	InGaAs	InGaAs
Photodiode responsivity (A/W)	No relevant differences, ~ 0.6 A/W		
Flip-chip assembly option, TX	Not feasible. Big absorption.	Feasible, but process dependent	Feasible
Flip-chip assembly option, RX		Not feasible. Big responsivity penalty	Feasible

980nm is the best choice for 802.3cz project

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Thank you!