Practical guidelines for specifying germanium and silicon for IR windows and lenses

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COHERENT

OUTLINE

- **Motivation for Work**
- **Germanium**
  - Overview
  - Refractive Index
  - Index Inhomogeneity
  - LWIR Transmission performance over temperature (20 C – 100 C)
- **Silicon**
  - Overview
  - Refractive Index
  - Index Inhomogeneity
  - MWIR Absorption at Room Temperature
- **Specification Examples**
- **Discussion/Conclusion**

MOTIVATION FOR WORK

- **Germanium & Silicon are important materials for MWIR optical systems & windows; Ge is also used for LWIR systems & windows**

- **Significant effort has been invested by the IR Materials Community to understand the performance characteristics of these two materials**

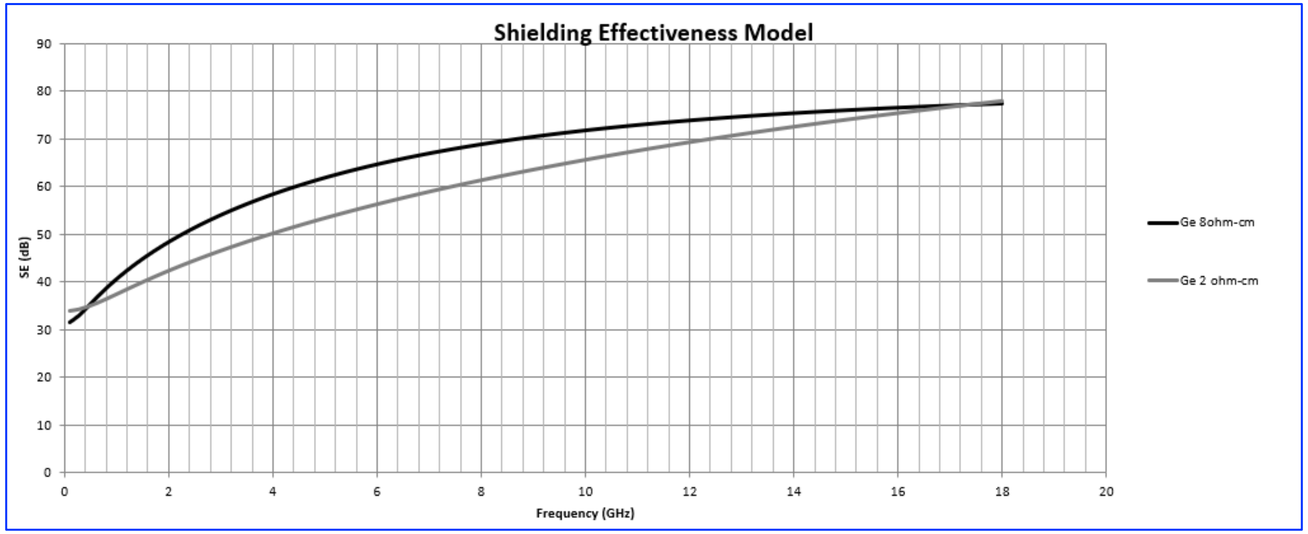
- **What does that mean for manufacturing? How do you properly specify to get the performance with you need without over-specifying (increased risk to cost & lead-time) or underspecifying (increased risk to performance)**

- **The following talk provides:**
  - Updated optical material performance characterization, representative of an optics manufacturing environment
  - Specification examples for manufacturing

GERMANIUM

OVERVIEW - GERMANIUM

- **Germanium is a crystalline material, available as a monocrystalline or polycrystalline substrate**
- **Diamond-cubic crystal structure; for most applications, no crystal orientation effects are expected**
- **Intentionally doped with n-type dopant to optimize IR transmission performance**
  - Typical applications: n-type, 5-40 ohm-cm bulk resistivity
  - EMI applications: n-type, 2 – 8 ohm-cm bulk resistivity
    - Lower-resistivity Ge windows can be thinner and provide the same EMI shielding benefit as thicker, higher-resistivity Ge windows
- **Measurement data in the following slides was performed on representative, optical grade, n-type, 5 – 40 ohm-cm samples**



8 ohm-cm, 0.6-inch-thick Ge window vs 2 ohm-cm, 0.2-inch-thick Ge window

REFRACTIVE INDEX MEASUREMENTS - GERMANIUM

- **Refractive index is a highly variable optical material property of Ge**
- **Measurements on prisms (via minimum angle deviation method) show that index variation is consistent with previously published studies on index of refraction of Ge**
- **For high volume optical assemblies in manufacturing, sufficient tolerance allotment is necessary to account for index variation. Routine measurement/re-comp to account for refractive index variation is not recommended:**
  - 1) traceability risk at high volume for Ge lenses & assemblies
  - 2) time consuming and expensive to continually adjust lens design via re-comp of lens radii

Wavelength (um)	Prism A 2014	Prism B 2014	Prism C 2021	Prism D 2021	Prism E 2021	Prism F 2023	Prism G 2023	Avg	Delta (max-min)
2.0	-	-	4.10569	4.10763	4.10799	4.10547	4.10781	4.10692	0.00252
3.0	4.04568	4.04444	4.04196	4.04397	4.04432	4.04199	4.04422	4.04380	0.00372
3.3	4.03872	4.03767	-	-	-	-	-	4.03819	0.00105
3.5	4.03333	4.03258	-	-	-	-	-	4.03295	0.00075
4.0	4.02555	4.02516	4.02214	-	-	4.02214	4.02400	4.02380	0.00341
4.5	4.02026	4.02003	-	-	-	-	-	4.02014	0.00023
5.0	4.01651	4.01637	4.01318	-	-	4.01318	4.01488	4.01482	0.00333

Index of refraction measurements performed by Coherent A&D on Ge samples, normalized to 20 C. Index variation in the third decimal place

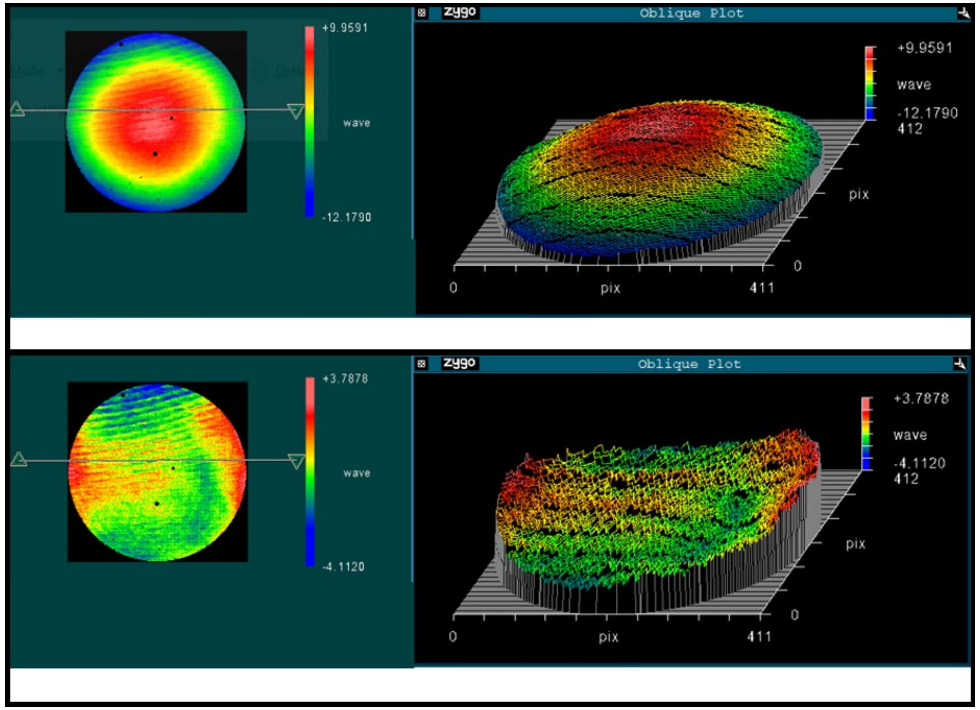
INDEX INHOMOGENEITY MEASUREMENTS - GERMANIUM

- **Refractive index inhomogeneity is an increasing concern for the Optical Design Engineer**
- **Measurements performed on 8-inch diameter, >2-inch-thick substrates, grown via the CZ method, were performed at 10.6 µm**
  - Measurements performed of test cavity, transmitted wavefront error (TWE) and reflected wavefront error of S1 and S2
  - Measurement post-processed; cavity, S1 and S2 measurements subtracted from the TWE measurement to yield wavefront map which isolates material impact to overall TWE
  - Calculated via the following equation:

$$Inhomogeneity\ (ppm) = \frac{TWE\ error\ (nm)}{Sample\ thickness\ (mm)}$$

- **Inhomogeneity is primarily dominated by power. Inhomogeneity due to high-order optical aberration is much lower**
- **Measurement results consistent with previously cited values for inhomogeneity in Germanium**

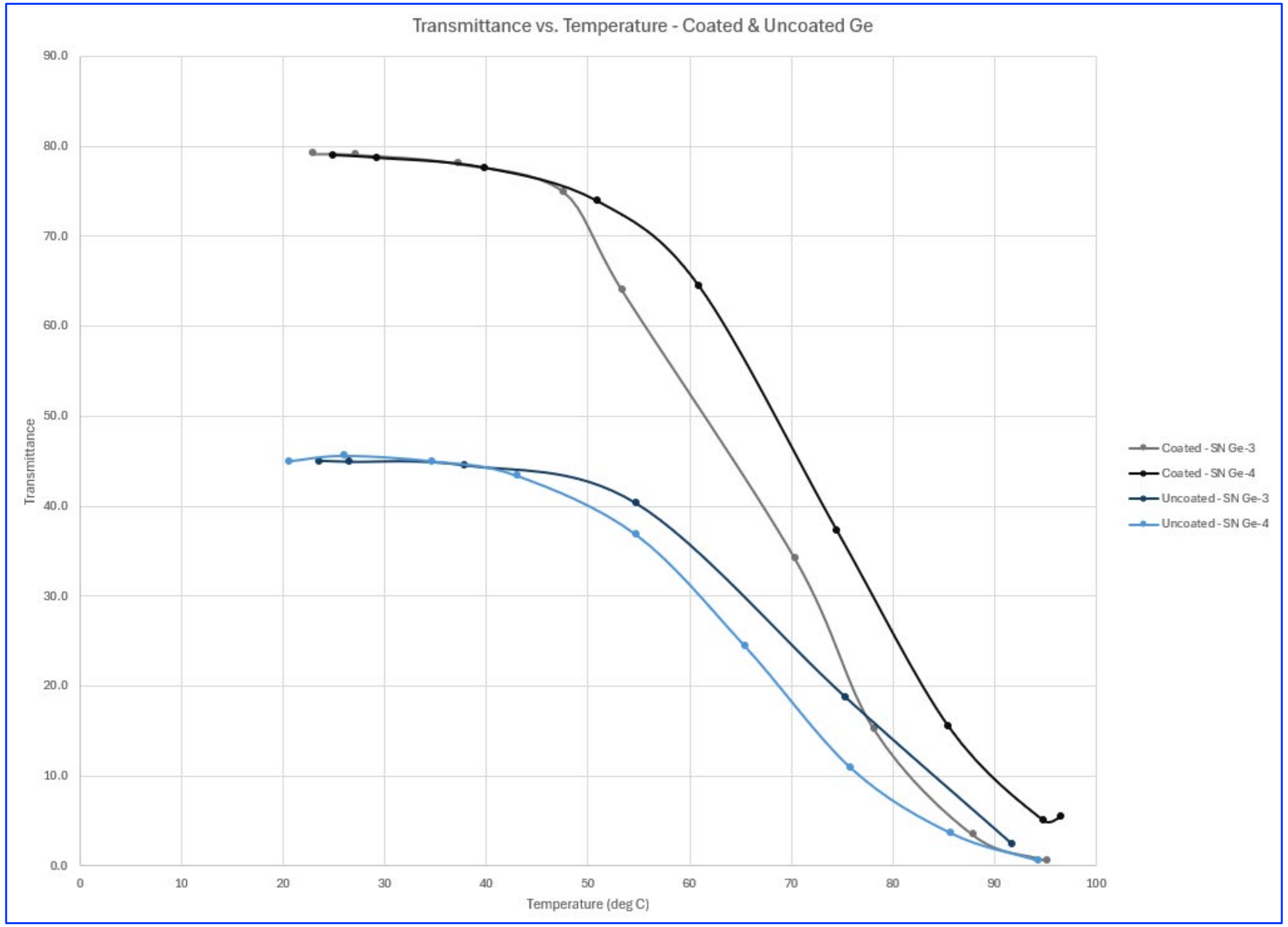
	Power Included	Power Subtracted
RMS Index Inhomogeneity (ppm)	57	11.8



Post-processed TWE maps for a germanium blank over an 8" aperture. Top figure is the resultant TWE with power included. Bottom figure is the resultant TWE with power subtracted

LWIR TRANSMISSION PERFORMANCE OVER TEMPERATURE - GERMANIUM

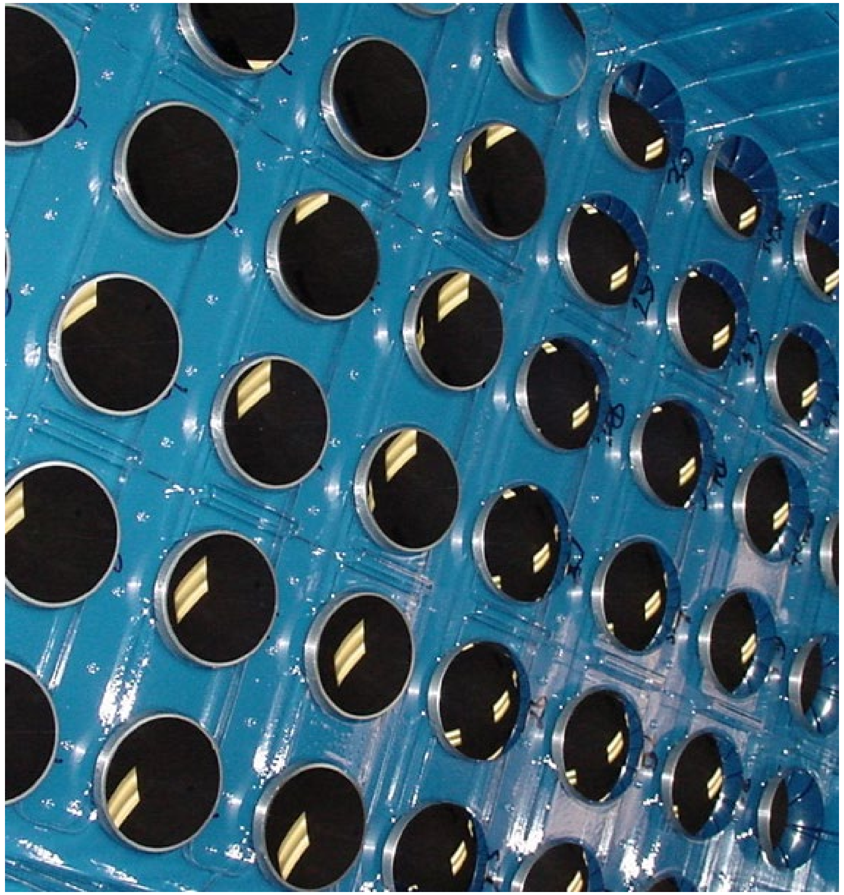
- **What is the usage temperature limit for Germanium?**
- **2-inch diameter, 0.4-inch-thick were conductively heated via a strip-heater applied & placed in intimate contact with the circumference of each sample**
- **Four samples tested**
  - Two samples were uncoated
  - Two samples contained standard, LWIR AR coatings
- **Measurements performed on Perkin Elemer FTIR spectrophotometer over a waveband of 8.5 µm – 11.5 µm. Transmission performance characterized from 20C – 100C.**
- **Transmission becomes impacted due to thermal absorption at 50C; at 90 C the material is essential opaque.**
- **AR coatings cannot overcome thermal absorption of the substrate**
- **Recommended usage temperature not to exceed 50 C to ensure maximum performance**



SILICON

OVERVIEW - SILICON

- **Silicon is a crystalline material, available as a monocrystalline or polycrystalline substrate**
- **Diamond-cubic crystal structure; for most applications, no crystal orientation effects are expected**
- **N-type most typically specified for IR applications using silicon**
  - 5 – 20 ohm-cm resistivity is recommended based on Coherent A&D experience
- **Measurement data in the following slides was performed on representative, optical grade, n-type, 5 – 20 ohm-cm samples**



REFRACTIVE INDEX MEASUREMENTS - SILICON

- **Similarly to Ge, refractive index is a highly variable optical material property of Si**
- **Measurements on prisms (via minimum angle deviation method) show that index variation is consistent with previously published studies on index of refraction of Si**
- **Same considerations as that for Ge:**
  - For high volume optical assemblies in manufacturing, sufficient tolerance allotment is necessary to account for index variation. Routine measurement/re-comp to account for refractive index variation is not recommended:
    - 1) traceability risk at high volume for Si lenses & assemblies
    - 2) time consuming and expensive to continually adjust lens design via re-comp of lens radii

Wavelength (um)	Prism A 2014	Prism B 2014	Prism C 2021	Prism D 2021	Prism E 2021	Prism F 2021	Prism G 2021	Avg	Delta (max-min)
2.0			3.45232	3.45215	3.45173	3.45158	3.45190	3.45193	0.00074
3.0	3.43251	3.43251	3.43185	3.43171	3.43133	3.43115	3.43150	3.43179	0.00137
4.0	3.42550	3.42541	3.42483	3.42475	3.42436	3.42413	3.42446	3.42478	0.00137
5.0	3.42232	3.42219	3.42157	3.42150	3.42112	3.42089	3.42119	3.42154	0.00143

Index of refraction measurements performed by Coherent A&D on Si samples, normalized to 20 C. Index variation in the third decimal place

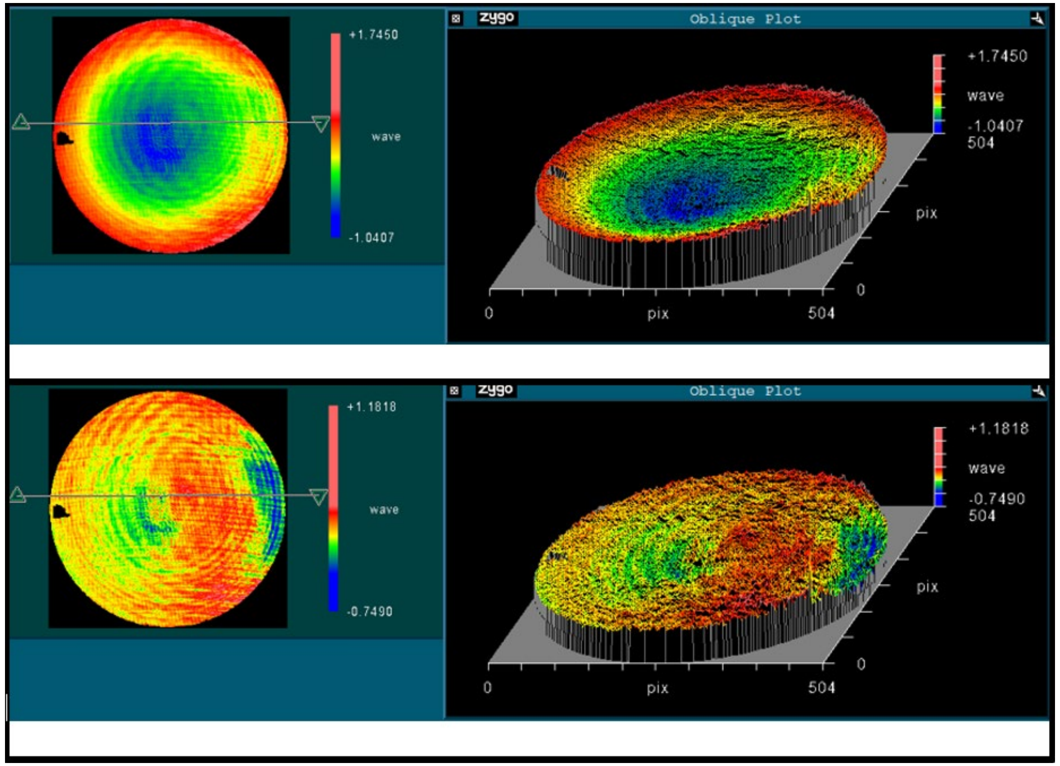
INDEX INHOMOGENEITY MEASUREMENTS - SILICON

- **Measurements performed on 4-inch diameter, 1.5-inch-thick substrates, grown via the CZ method, were performed at 3.39 µm**
  - Measurements performed of test cavity, transmitted wavefront error (TWE) and reflected wavefront error of S1 and S2
  - Measurement post-processed; cavity, S1 and S2 measurements subtracted from the TWE measurement to yield wavefront map which isolates material impact to overall TWE
  - Calculated via the following equation:

$$Inhomogeneity\ (ppm) = \frac{TWE\ error\ (nm)}{Sample\ thickness\ (mm)}$$

- **Inhomogeneity for Si is lower than that of Ge**
  - Inhomogeneity measurements also show power to be the dominant optical aberration due to inhomogeneity
- **Measurement results consistent with previously cited values for inhomogeneity in Silicon**

	Power Included	Power Subtracted
RMS Index Inhomogeneity (ppm)	5.63	1.73



Post-processed TWE maps for a silicon blank over a 4" aperture. Top figure is the resultant TWE with power included. Bottom figure is the resultant TWE with power subtracted

MWIR ABSORPTION AT ROOM TEMPERATURE - SILICON

- **Silicon absorption was characterized in the MWIR at room temperature on an uncoated sample**
- **Sample thickness: 2.177 cm**
- **Multiple transmission measurements performed on a Lambda 9 and FTIR spectrophotometer over a waveband of 3.3 – 5.5 µm and averaged**
- **Absorption calculated via the STAC Equation:**

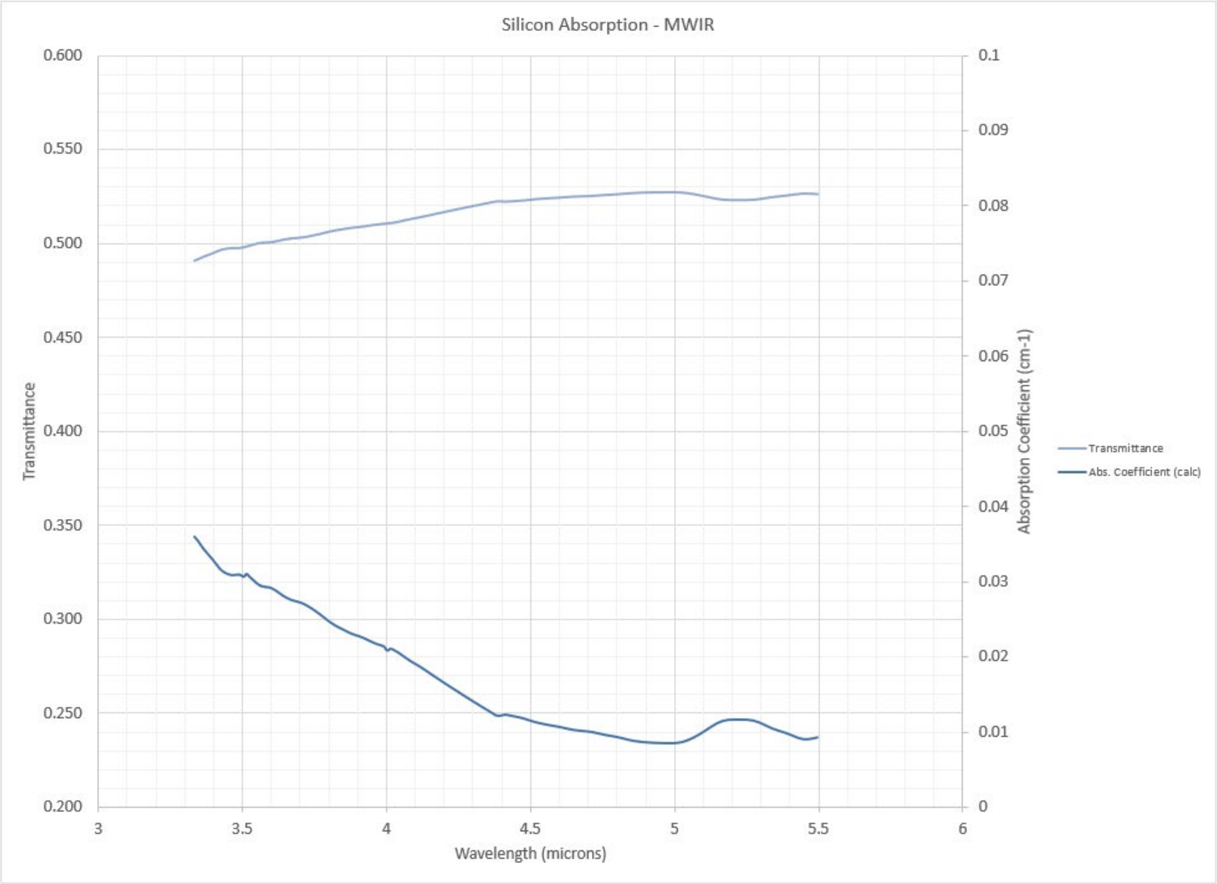
$$\alpha = -\left(\frac{1}{t}\right)\ln\left\{\left[\frac{(1-r)^4}{4r^4T^2}+\frac{1}{r^2}\right]^{\frac{1}{2}}-\frac{(1-r)^2}{2r^2T}\right\}$$

Where: r is the reflectivity {$r = (n-1)^2/(n+1)^2$}

n is the refractive index

t is the thickness in cm

T is the measured transmittance



SPECIFICATION EXAMPLES DISCUSSION/CONCLUSION

SPECIFICATION EXAMPLES (*FOR MANUFACTURING)*

Germanium

Application – Optical Lens

Material: Germanium

Monocrystalline, optical grade, n-type, 5-40 ohm-cm, <100> or <111> crystal orientation

For reference only: Index of refraction: *specify wavelength(s) of interest and cite nominal values for refractive index*

Application – Optical grade optic or window

Material: Germanium

Monocrystalline or polycrystalline, optical grade, n-type, 5-40 ohm-cm

Application – EMI grade optic or window

Material: Germanium

Monocrystalline or polycrystalline, EMI grade, n-type, 2-8* ohm-cm

*NOTE: resistivity range for EMI grade may be narrowed if a given application calls for it. For example, the range of interest may be 3-5 ohm-cm or 5-8 ohm-cm, depending on the application needs.

Silicon

Application – Optical Lens

Material: Silicon

Monocrystalline, optical grade, n-type, 5 – 20 ohm-cm, <100> or <111> crystal orientation

For reference only: Index of refraction: *specify wavelength(s) of interest and cite nominal values for refractive index*

Application – Optical grade optic or window

Material: Silicon

Monocrystalline or polycrystalline, optical grade, n-type,

5 – 20 ohm-cm

DISCUSSION & CONCLUSION

- Coherent A&D has performed optical material property characterization for germanium and silicon that is representative of how these properties might be measured or certified in a production manufacturing environment
- Both materials have optical property variation that must be duly considered in IR system design
- Understanding the variation and performance limits of these materials ensures system performance expectations can be met
- However, how these properties might be measured, or how those measurements might impact routine manufacturing are important considerations as well, especially if a given Program is expected to reach higher volumes
- The data and specification recommendations provided aim to further the understanding of optical performance of Ge and Si, as well as how verification of those optical properties might impact production manufacturing

Thank you!

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