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# SiGe formation by Ge implant+high power Anneal Raman data summary

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# Outline

- Background: samples conditions, TEM and SIMS analysis
- Raman analysis: set-up and reference data
- Example of Raman spectrum
- Analysis position
- Summary of center analysis
- Focus on wf 01 and wf 02
- Summary of edge analysis
- Summary of cross line and depht profile analysis
- Focus on wf 05 COND1, COND2, COND3
- Conclusions

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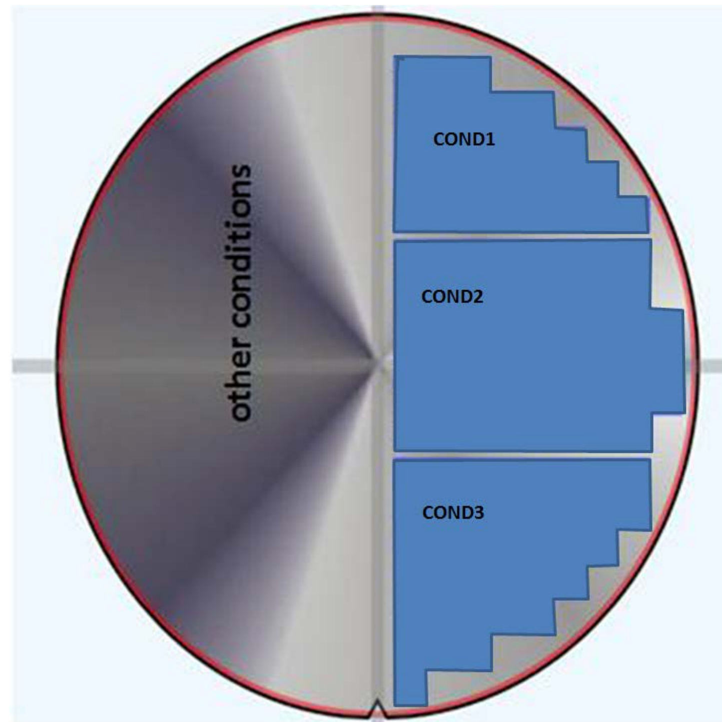
# Samples conditions

- Process conditions:

| Ge implant | Ge anneal | wf# |
|---|---|---|
| 50 keV 3.5 E17 atoms/cm^2 | High temp – single step | 01 |
| 50 keV  5E17 atoms/cm^2 | High temp – double step | 02 |
| 50 keV 3.5 E17 atoms/cm^2 | laser anneal | 05 |

- Focus on wf 05: laser thermal annealing




| COND 1 | COND 2 | COND 3 |
|---|---|---|
| 2X | 3X | 30X |

Relative energy density, for each condition

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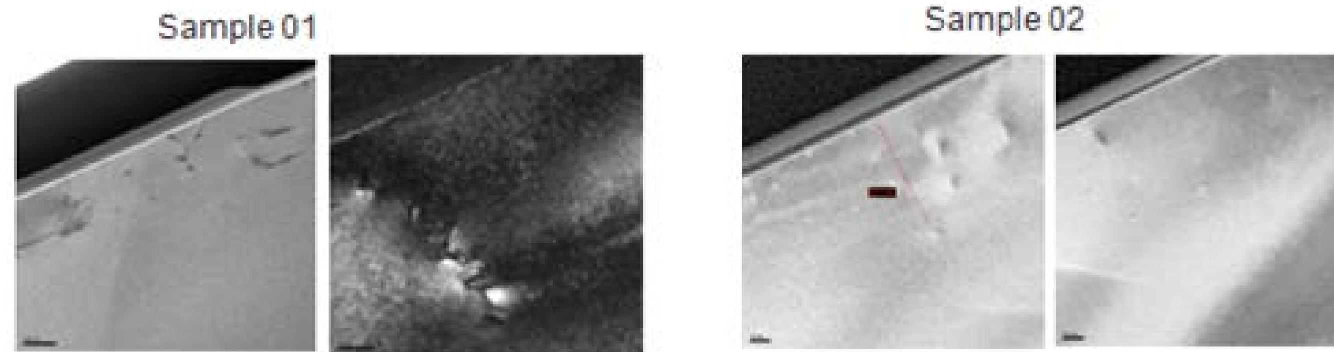
# TEM analysis

## Wf 01 and wf 02




Residuals extended defects are observed when single furnace is used;
Better results are observed on sample 02 (double anneal)

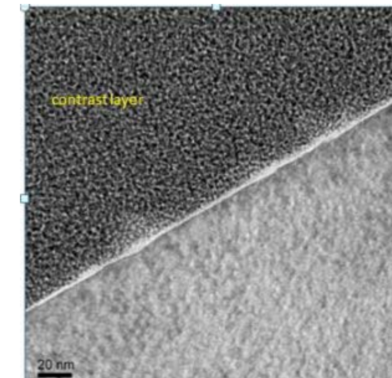
## wf 05

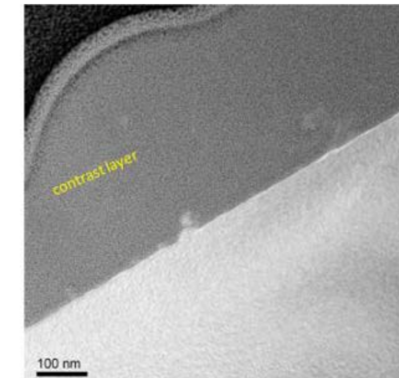
- COND1 sample shows defects and silicon extrusions in the silicon surface;
the bulk lattice is well crystallized;

- COND2 and COND3 both show a good silicon crystallization;

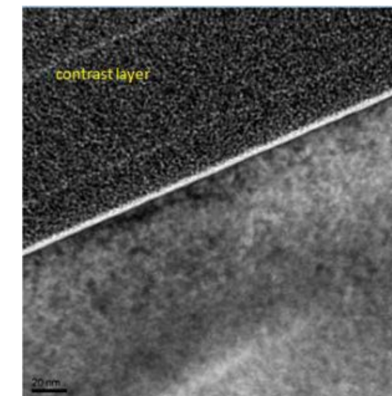
- All the three sample show an oxide layer grown in the silicon surface.

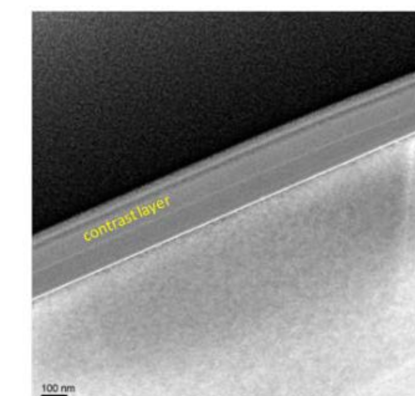
Cond 1



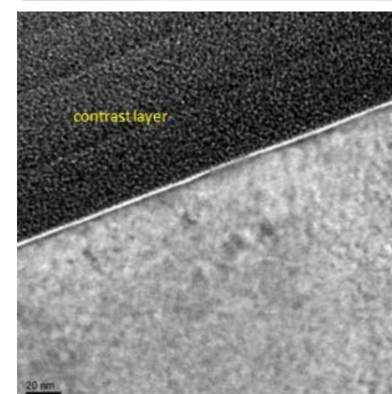



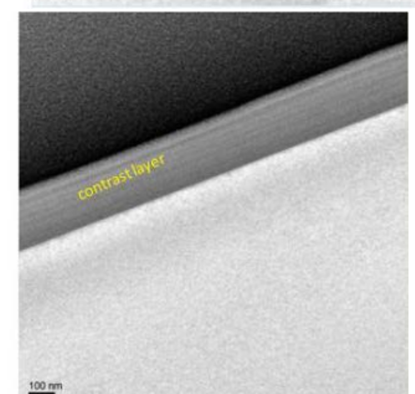

Cond 2




Cond 3



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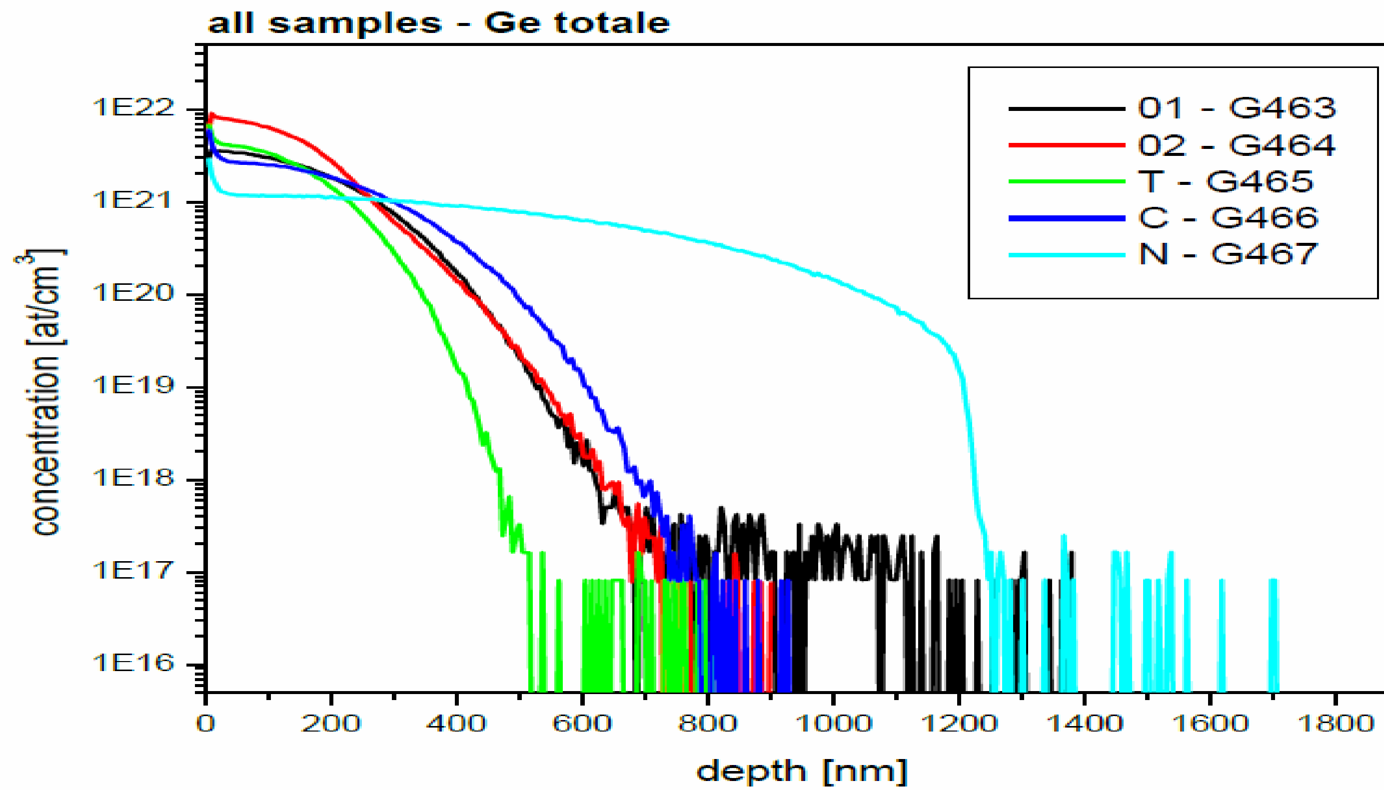
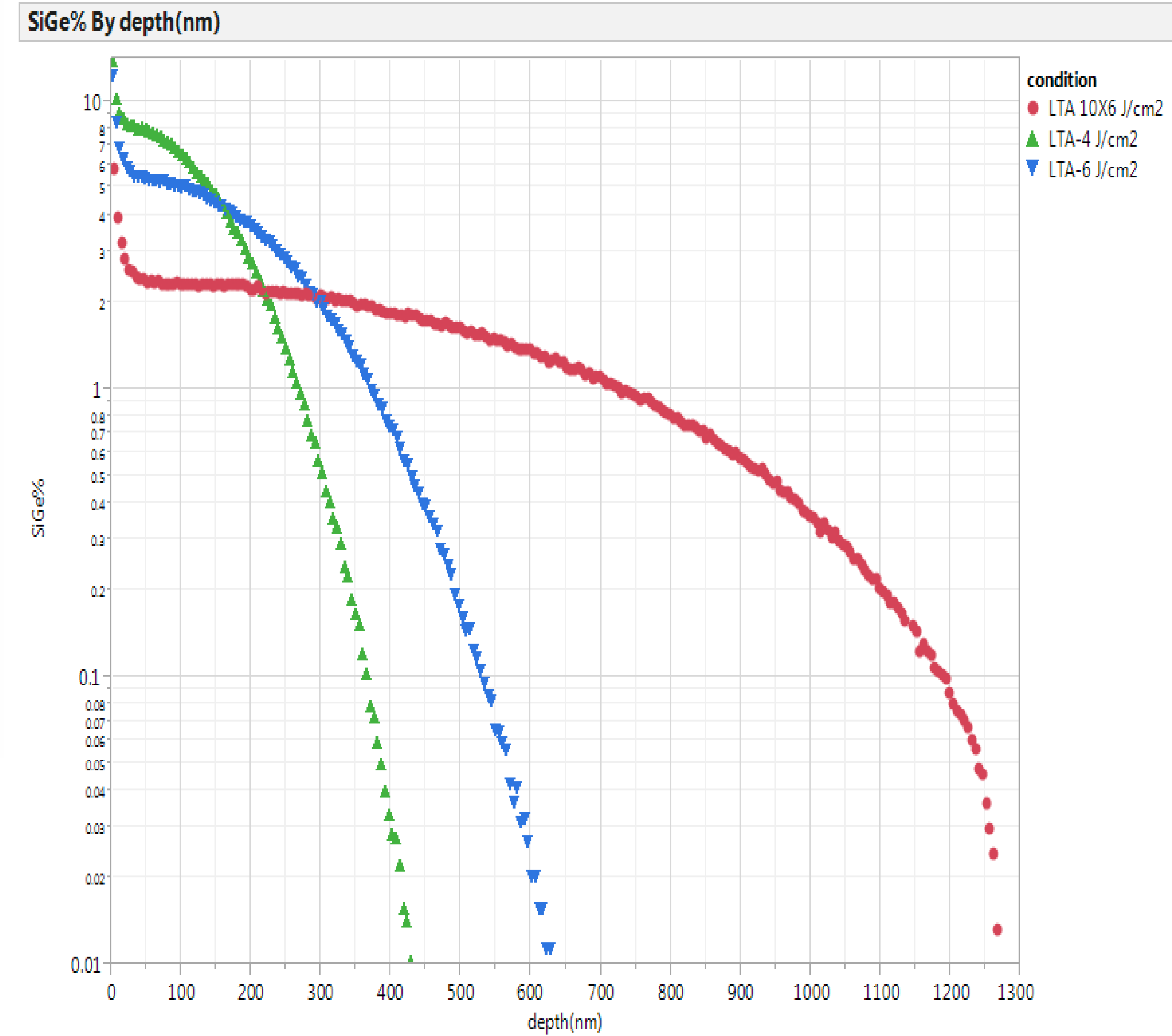
# SIMS analysis




The total calculated dose is systematically lower than the implanted one;
The samples annealed in furnaces (01, 02) show Ge diffusion with a concentration greater than $10^{20}$ up to a depth of 400/600 nm;
Deeper Ge diffusion is obtained by using LTA; the sample N (condition LTA3) showed a Ge diffusion of about 1 um




| sample | SIMS Ge dose at/cm^2 |
| --- | --- |
| Wf 01 | (7.4 ± 0.7) E 16 |
| Wf 02 | (1.4 ± 0.1) E 17 |
| Wf 05 Cond1 | (7.2+/-0.7)x10^16 |
| Wf 05 Cond2 | (7.3+/-0.7)x10^16 |
| Wf 05 Cond3 | (7.6+/-0.7)x10^16 |

Density of silicon 4.995E+22 Atoms/cm^3

Ge concentration at the surface ~ 10% in wf 01, ~20% in wf 02, ~10-5% in wf 05.

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# Raman Analysis: set-up and reference data

- UV (355 nm) and Green (532 nm) Laser were used
- Objective lens: UV 40x – Green 100x
- Laser power: UV 50% – Green 10%
- Penetration Laser: ~510 nm for Green laser, ~10 nm for UV laser
- Type of measurement: StreamLine range 400nm-1800 nm, Depth profile range 1,9um-2,9 um
- Silicon lattice: Diamond Cubic. Lattice spacing: 0,543 nm
- Germanium lattice: Diamond Cubic. Lattice spacing: 0,566 nm
- Lattice mismatch: ε = (|aSi – aGe|/aSi)*100 = 4.2%

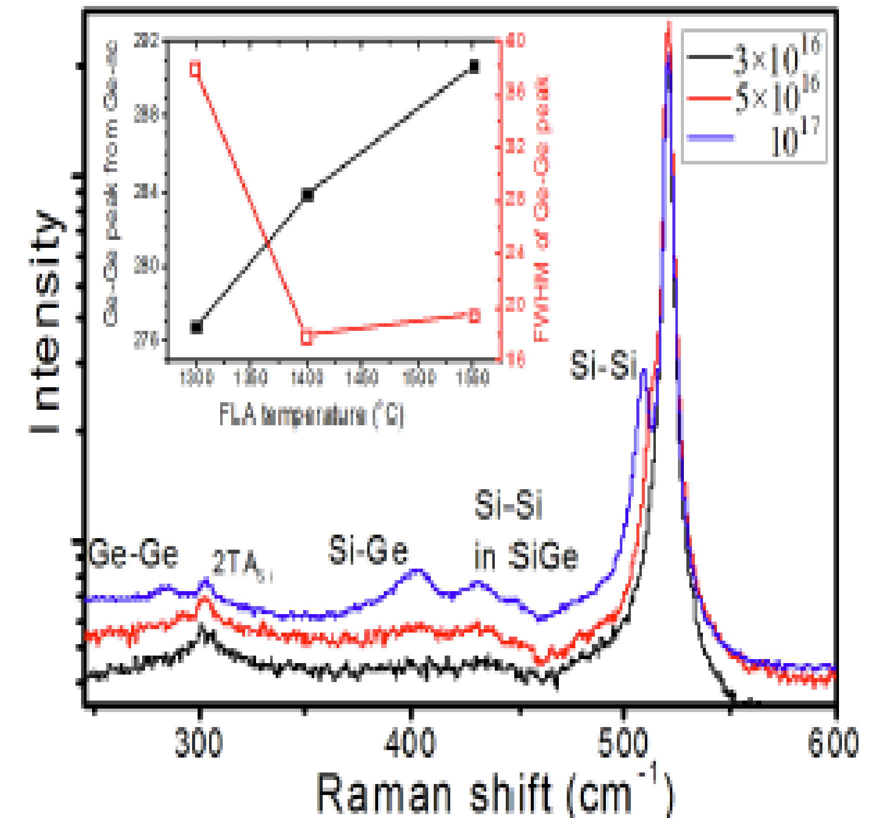
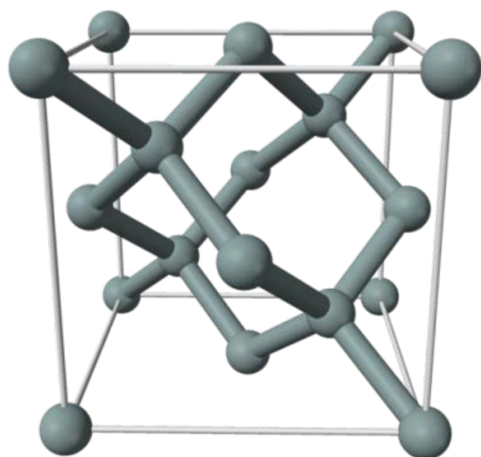
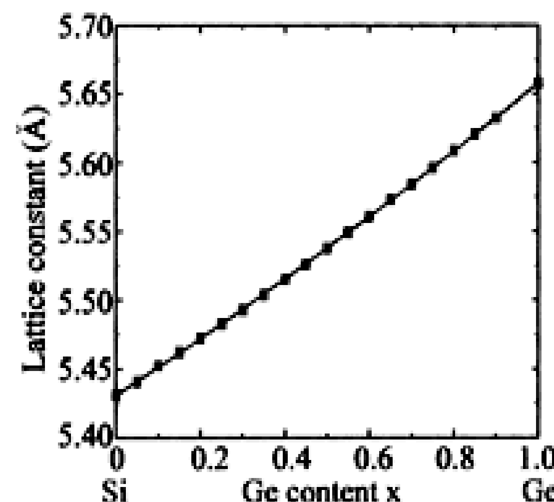



Fig. 2. μ-Raman spectra obtained from the flash lamp annealed samples for 20 ms at 1400 °C. Several characteristic peaks of $Si_{1-x}Ge_x$ are clearly depicted. The inset shows the change of the Ge–Ge related phonon mode position and FWHM as the function of annealing temperature.

| From reference | Peak position Si-Si bulk | 520,5 cm^-1 |
|---|---|---|
| | Peak position Si-Si in SiGe | 508 cm^-1 |
| | Peak position Si-Ge in SiGe | 403 cm^-1 |
| | Peak position Ge-Ge | 286 cm^-1 |

Reference: Fabrication of SiGe alloy on Silicon by Ge-Ion-Implantation and Short-Time-Annealing, K.Gao et al., Acta phys. Pol. Vol 123 (2013)



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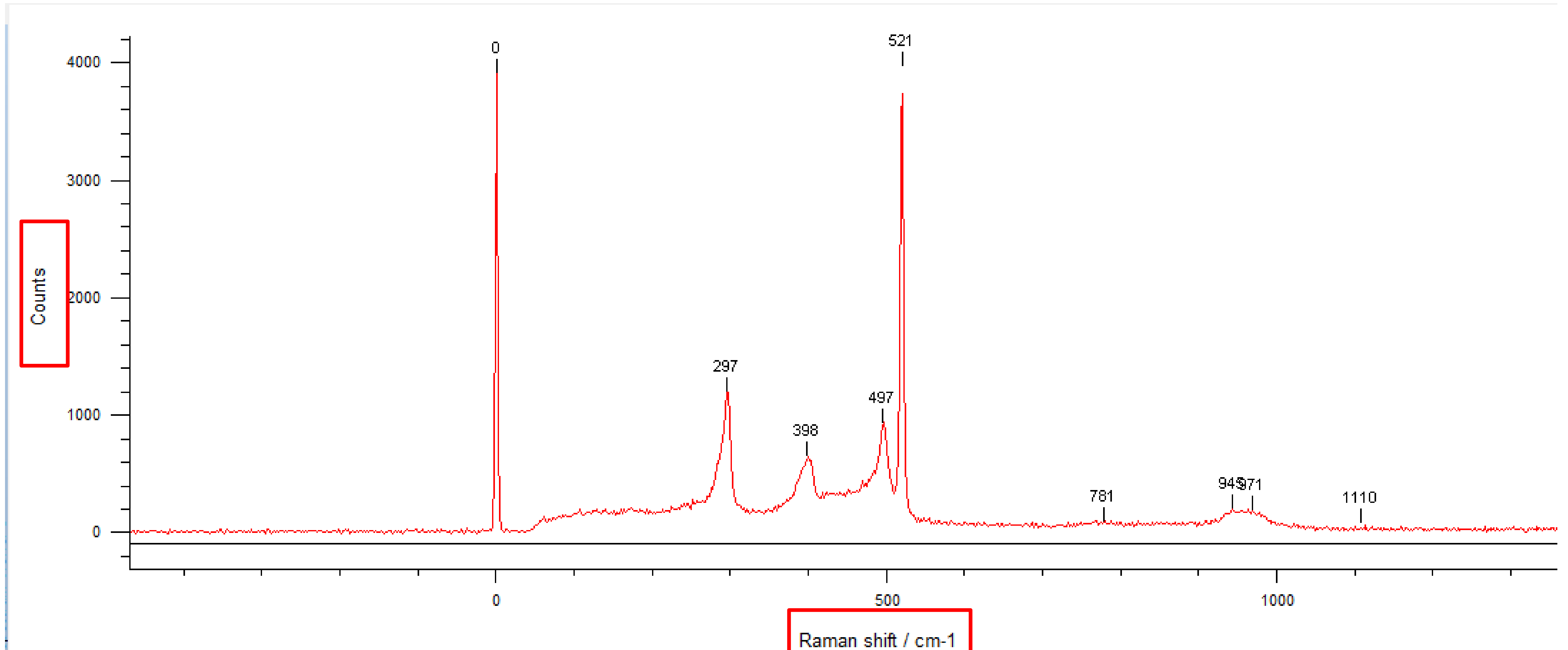
# Example of Raman Sprectrum




| Peak no. | Centre | Height | Width | Area | Absolute inten... | Low edge | High edge |
|---|---|---|---|---|---|---|---|
| 2 | 0.22455 | 3931.08 | 2.36497 | 11523.2 | 3942.92 | -13.6465 | 15.9531 |
| 5 | 296.945 | 1005.53 | 12.8394 | 51151.1 | 1208.94 | 248.91 | 330.768 |
| 6 | 398.495 | 388.107 | 20.2412 | 46281.1 | 659.827 | 338.34 | 417.422 |
| 7 | 496.847 | 582.443 | 11.399 | 53818 | 949.028 | 445.477 | 508.707 |
| 8 | 520.813 | 3727 | 4.4627 | 34582.4 | 3999.22 | 510.559 | 545.668 |
| 10 | 780.965 | 34.1019 | 3.48693 | 3115.52 | 103.207 | 772.863 | 792.549 |
| 11 | 944.882 | 53.3498 | 3.4744 | 12367.5 | 209.95 | 904.357 | 953.545 |
| 12 | 971.251 | 46.6173 | 3.16284 | 12921.8 | 196.035 | 955.297 | 1000.69 |
| 13 | 1109.67 | 54.28 | 6.85547 | 581.256 | 92.8876 | 1118.18 | 1125.04 |

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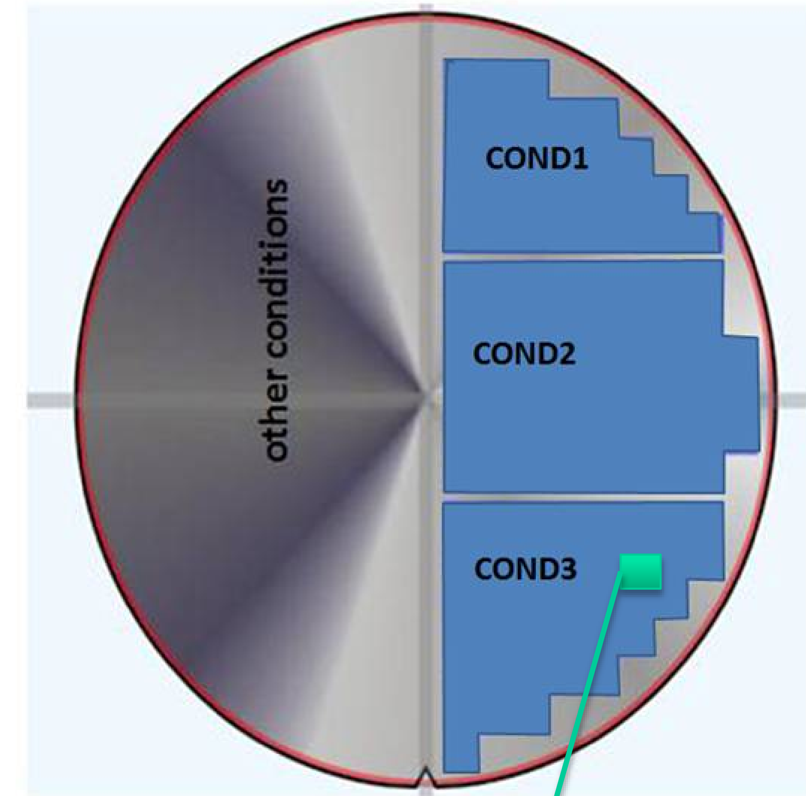
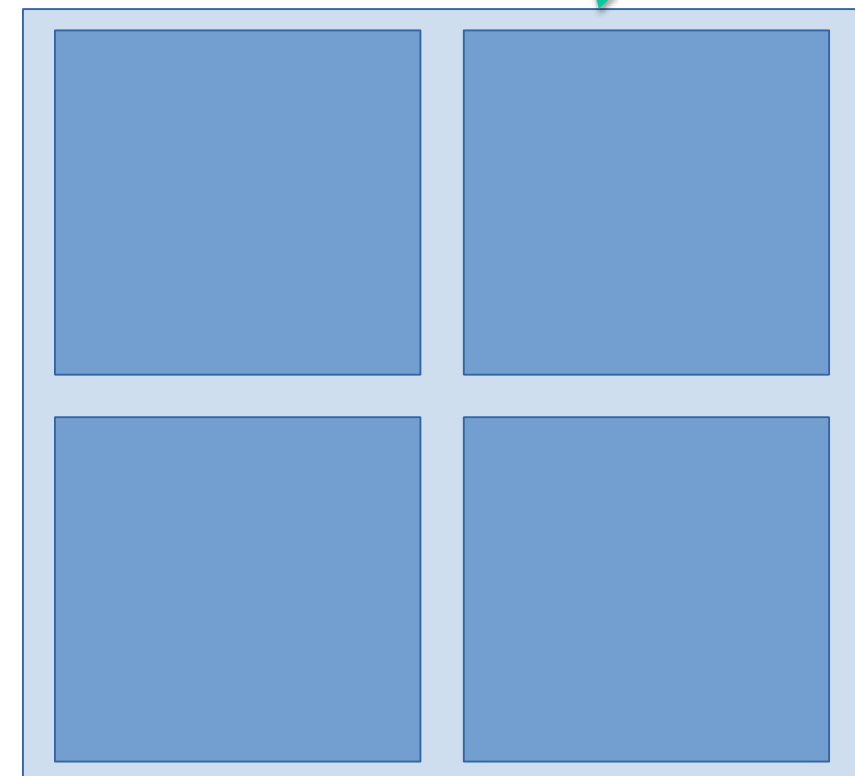
# Analysis positions

- For the wafer 01 and 02 (without any pattern) the analysis was taken at the center of the wafer;
- For the wafer 05 the analys was taken in different points of the pattern. The pattern is made with several squares (of the order of ~1-10 $cm^2$), due to the laser annealing process.



- **Positions of the analysis:**
  - Center
  - Edge
  - Crossline
  - Depth profile

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# Summary of the center analysis

GREEN LASER:

- ➔ wf 05 COND1 and wf 05 COND2: only the Si-Si peak is visible.
- ➔ Wf 01: the Si-Ge is weakly visible around 390 $cm^{-1}$
- ➔ wf 05 COND3: the Si-Si peak, the Si-Ge peak and the Ge-Ge peak.
- ➔ *The wf 02 is the only sample that shows all the peaks similar to the reference.*
- ➔ The width of the Si-Si peaks are narrow (between 7 and 5) and decrease increasing the thermal power in the process condition

| wf | Process condition | # peak | Peak position (Raman shift $cm^{-1}$) |
|---|---|---|---|
| Wf 02 | High temp - double step | 1st | 302,585 |
| | | 2nd | 401,39 |
| | | 3rd | 512,52 |
| | | 4th | 520,58 |

UV LASER:

- ➔ Only one peak is visible for each sample.
- ➔ Every peak shows a very large width (between 60 and 25) revealing amorphous phases.

| wf | Process condition | Peak position (Raman shift $cm^{-1}$) |
|---|---|---|
| 01 | High temp – single step | 513.285 |
| 02 | High temp – double step | 507,401 |
| 05 COND1 | Laser anneal 2x | 515,704 |
| 05 COND2 | Laser anneal 3x | 514,345 |
| 05 COND3 | Laser anneal 30x | 516,929 |

| From reference article | Peak position Si-Si bulk | 520,5 | Peak position Si-Ge in SiGe | ~400 |
|---|---|---|---|---|
| | Peak position Si-Si in SiGe | ~500 | Peak position Ge-Ge | ~300 |

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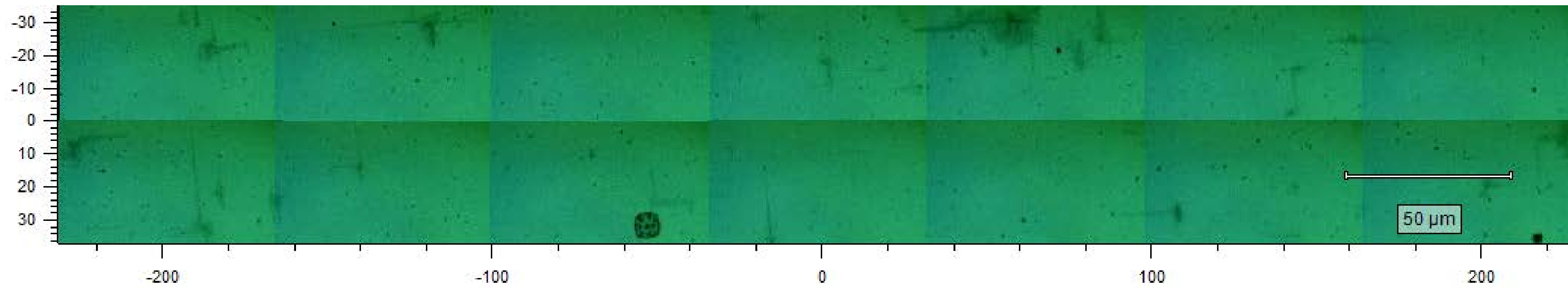
# Focus on Wf 01




- Process condition: Ge implantation + furnace annealing
- Measurement: streamLine 200 um, step 0.5 um, 1 sec exposure time

| UV | Peak Position | Height | Width |
|---|---|---|---|
| | 513.285 | 40.4998 | 9.17186 |
| **GREEN** | **Peak Position** | **Height** | **Width** |
| | 0.17377 | 486.68 | 2.97384 |
| | 57.873 | 23.6508 | 6.97217 |
| | 387.376 | 29.1492 | 2.22819 |
| | 519.231 | 6169.36 | 7.03638 |
| | 963.987 | 196.817 | 57.9348 |

Raman spectrum of wf 01 (green laser)

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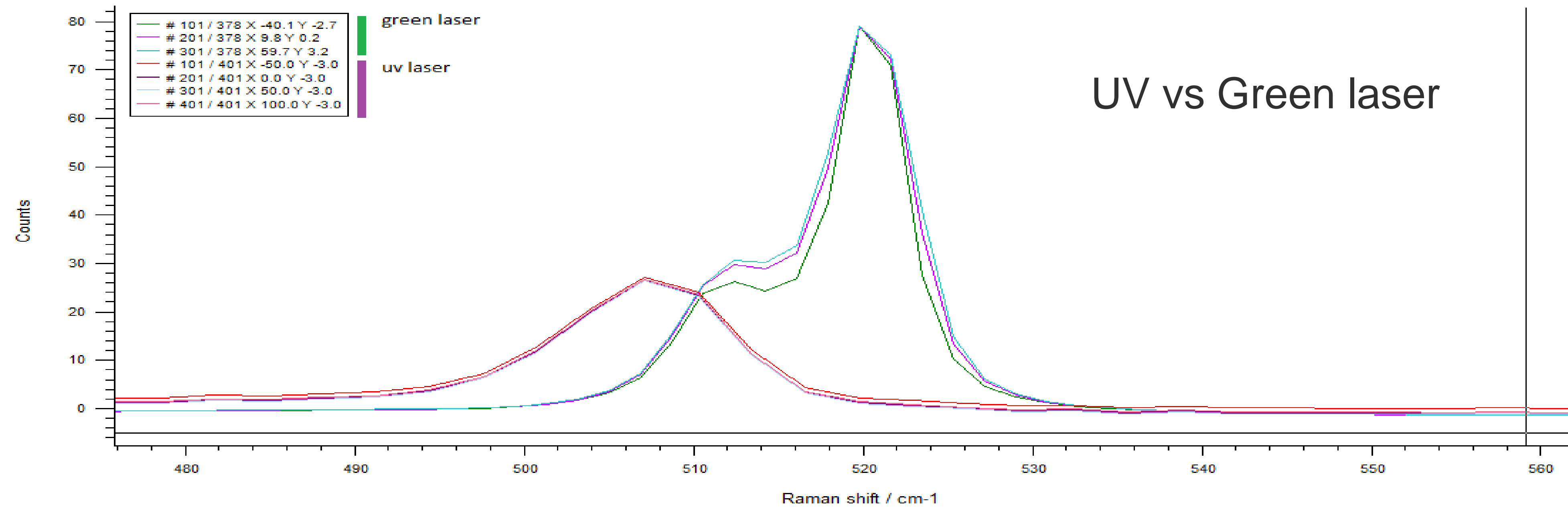
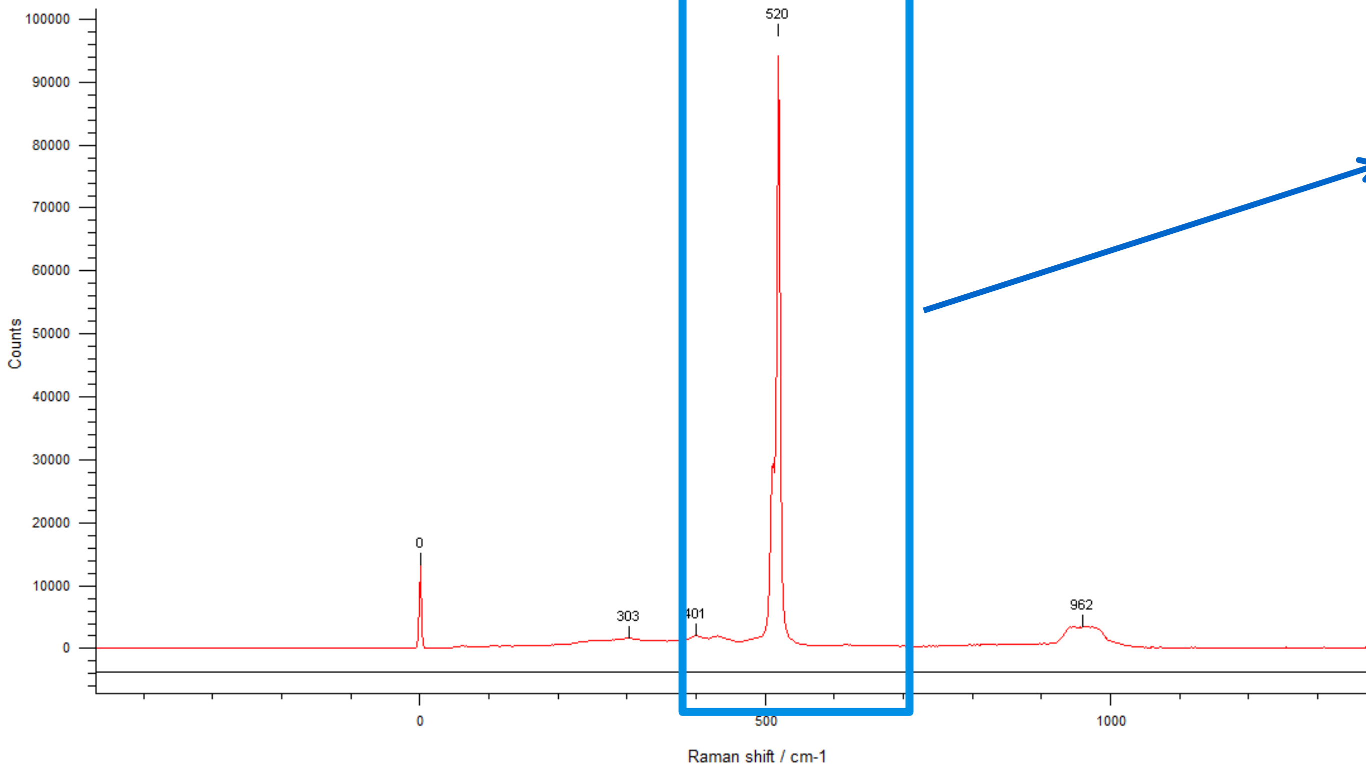
# Focus on Wf 02

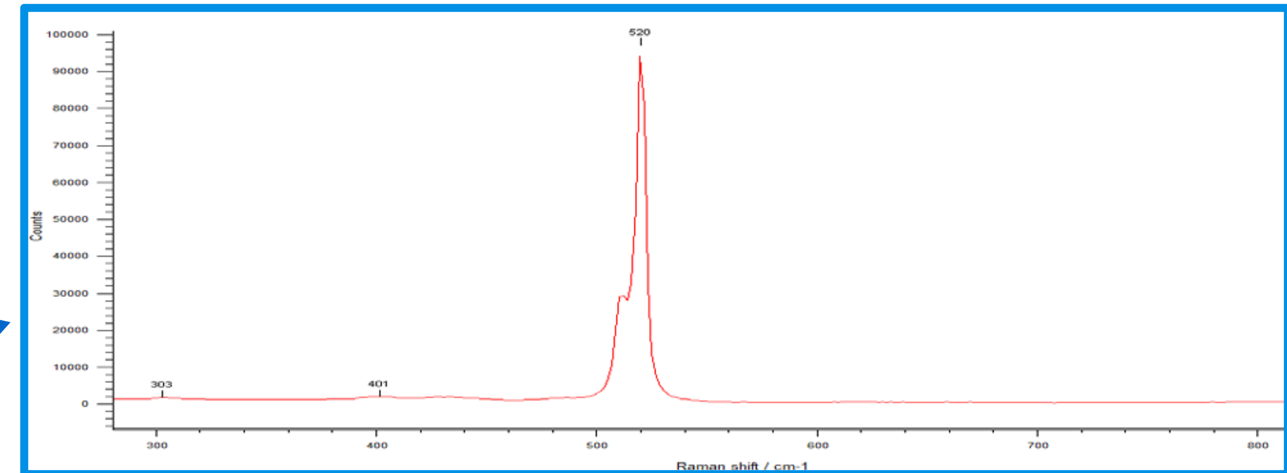
- Process condition: Ge implantation x2 + furnace annealing x2
- Measurement: streamLine 200 um, step 0.5 um, 1 sec exposure time




Raman spectrum of wf 02 (green laser) and zoom of the main peak:




| Peak no. | Centre | Height | Width | Area | Absolute inten... | Low edge | High edge |
|---|---|---|---|---|---|---|---|
| 12 | 0.19572 | 10632.9 | 2.93024 | 78686.8 | 13324.8 | -25.5156 | 2.1543 |
| 13 | 302.595 | 717.825 | 37.253 | 430525 | 1733.13 | 47.4063 | 349.686 |
| 14 | 401.39 | 805.639 | 16.8339 | 270660 | 2064.15 | 351.576 | 447.344 |
| 15 | 520.475 | 96794.9 | 5.29261 | 1.10228e+006 | 97740.9 | 449.211 | 598.959 |
| 18 | 962.34 | 3294.69 | 62.3543 | 422274 | 3454.54 | 727.941 | 1088.97 |




| | Peak position | Width | Height |
|---|---|---|---|
| Green curve 1 | 520,583 | 6,04101 | 96338,77 |
| Green curve 2 | 512,521 | 7,86846 | 3884,498 |
| Green curve 3 | 302,585 | 37,253 | 717,825 |
| Green curve 4 | 401,39 | 26,83 | 805 |
| UV | 507,401 | 9,58473 | 28,4308 |

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# Summary of the edge analysis

GREEN LASER:

- ➔ COND1, COND2 and COND3 show all the peaks in areas similar to the reference.
- ➔ The width of Si-Si bulk peaks is narrow and close to 4. The other peaks show broader width.

UV LASER:

- ➔ COND1 shows only one peak, really close in value to the Si-Si in SiGe peak, and very large in width.
- ➔ COND2 and COND3 shows two peaks with narrow width

| wf | Process condition | Peak position (Raman shift $cm^{-1}$) |
|---|---|---|
| 05 COND2 | Laser anneal 3x | 511,424 |
| | | 495,099 |
| 05 COND3 | Laser anneal 30x | 495,579 |
| | | 509,158 |

| From reference article | Peak position Si-Si bulk | 520,5 | Peak position Si-Ge in SiGe | ~400 |
|---|---|---|---|---|
| | Peak position Si-Si in SiGe | ~500 | Peak position Ge-Ge | ~300 |



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# Summary of the cross-line and depth profile analysis

GREEN LASER for Cross-line:

- ➔ The width of the edge's square slowly decreases, increasing the power of laser annealing. In the COND3 the squares are overlapped.
- ➔ The peaks follow the same trend depending on position. The change in width of all the peaks shows the amorphous phase along the edge.

GREEN LASER for Depth-profile:

- ➔ The width and the position remain constant and the intensity decreases with the increasing Z. The intensity of Si-Si peak is more than the others.

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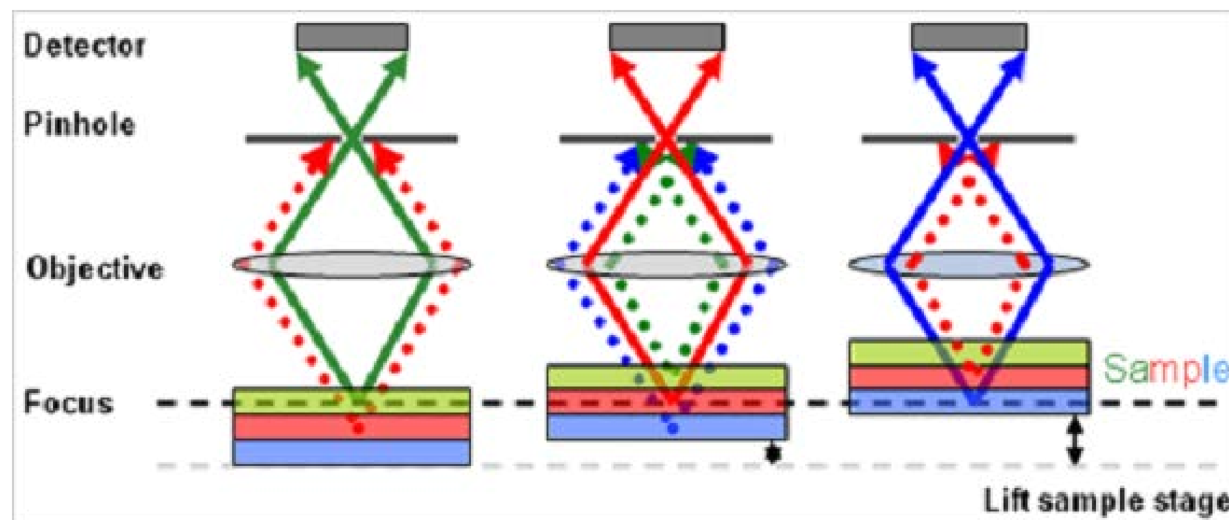


UV LASER:

- ➔ The peaks in cross line measurements show the same trend of green laser measurements.

| From reference article | Peak position Si-Si bulk | 520,5 | Peak position Si-Ge in SiGe | ~400 |
|---|---|---|---|---|
| | Peak position Si-Si in SiGe | ~500 | Peak position Ge-Ge | ~300 |



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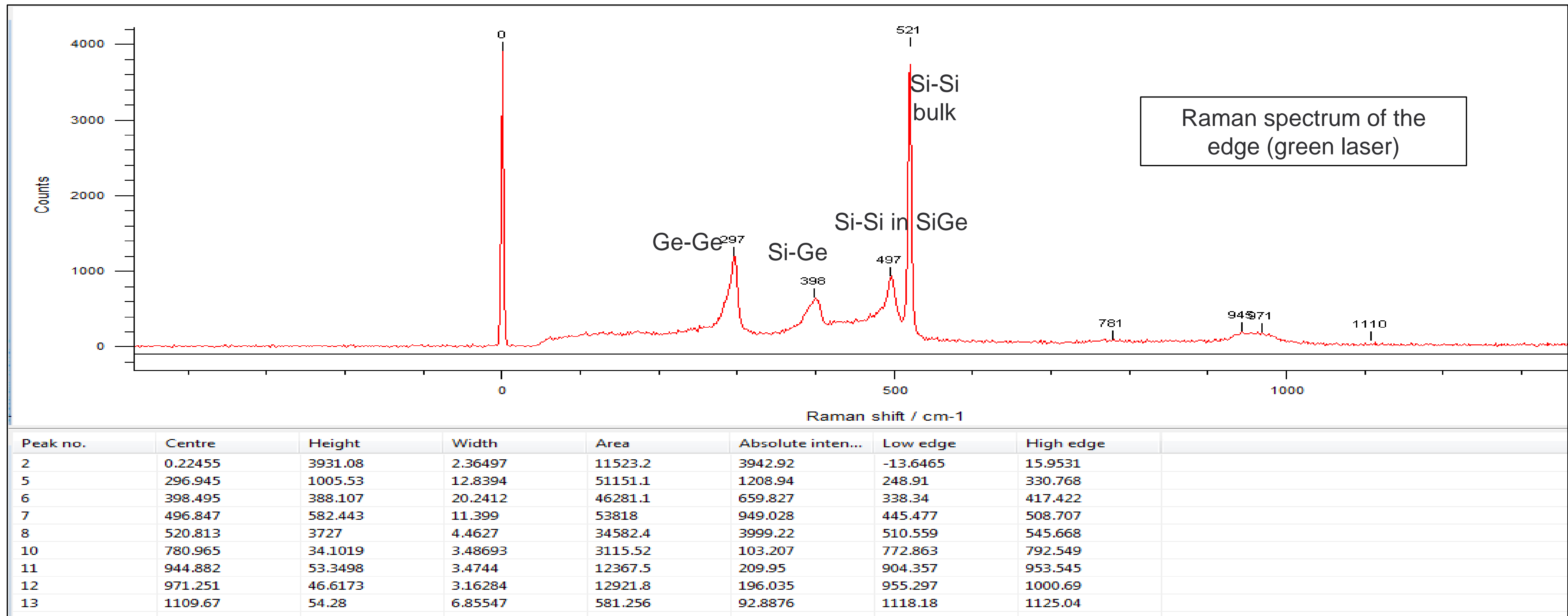
# Focus on Wf 05 COND1

- Process condition: Ge implantation + Laser anneal 2x
- Measurement:
  - center square, streamLine1000 um, step 1 um, exposure time 1s
  - edge square, streamLine 900 um, step 5 um, exposure time 1s
  - crossline, streamLine 400 um, step 0.5 um, exposure time 1s
  - depth profile, step 0.1 um, exposure time 1s, Z center 1,9 um, Z edge 2,9 um




| Peak no. | Centre | Height | Width | Area | Absolute inten... | Low edge | High edge |
|---|---|---|---|---|---|---|---|
| 2 | 0.22455 | 3931.08 | 2.36497 | 11523.2 | 3942.92 | -13.6465 | 15.9531 |
| 5 | 296.945 | 1005.53 | 12.8394 | 51151.1 | 1208.94 | 248.91 | 330.768 |
| 6 | 398.495 | 388.107 | 20.2412 | 46281.1 | 659.827 | 338.34 | 417.422 |
| 7 | 496.847 | 582.443 | 11.399 | 53818 | 949.028 | 445.477 | 508.707 |
| 8 | 520.813 | 3727 | 4.4627 | 34582.4 | 3999.22 | 510.559 | 545.668 |
| 10 | 780.965 | 34.1019 | 3.48693 | 3115.52 | 103.207 | 772.863 | 792.549 |
| 11 | 944.882 | 53.3498 | 3.4744 | 12367.5 | 209.95 | 904.357 | 953.545 |
| 12 | 971.251 | 46.6173 | 3.16284 | 12921.8 | 196.035 | 955.297 | 1000.69 |
| 13 | 1109.67 | 54.28 | 6.85547 | 581.256 | 92.8876 | 1118.18 | 1125.04 |

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# Wf 05 COND1

CROSS LINE: width vs distance
Width of the Silicon peak

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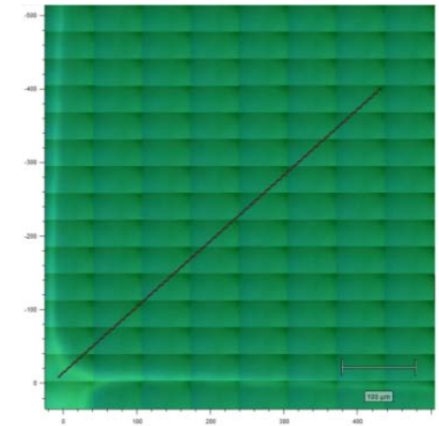
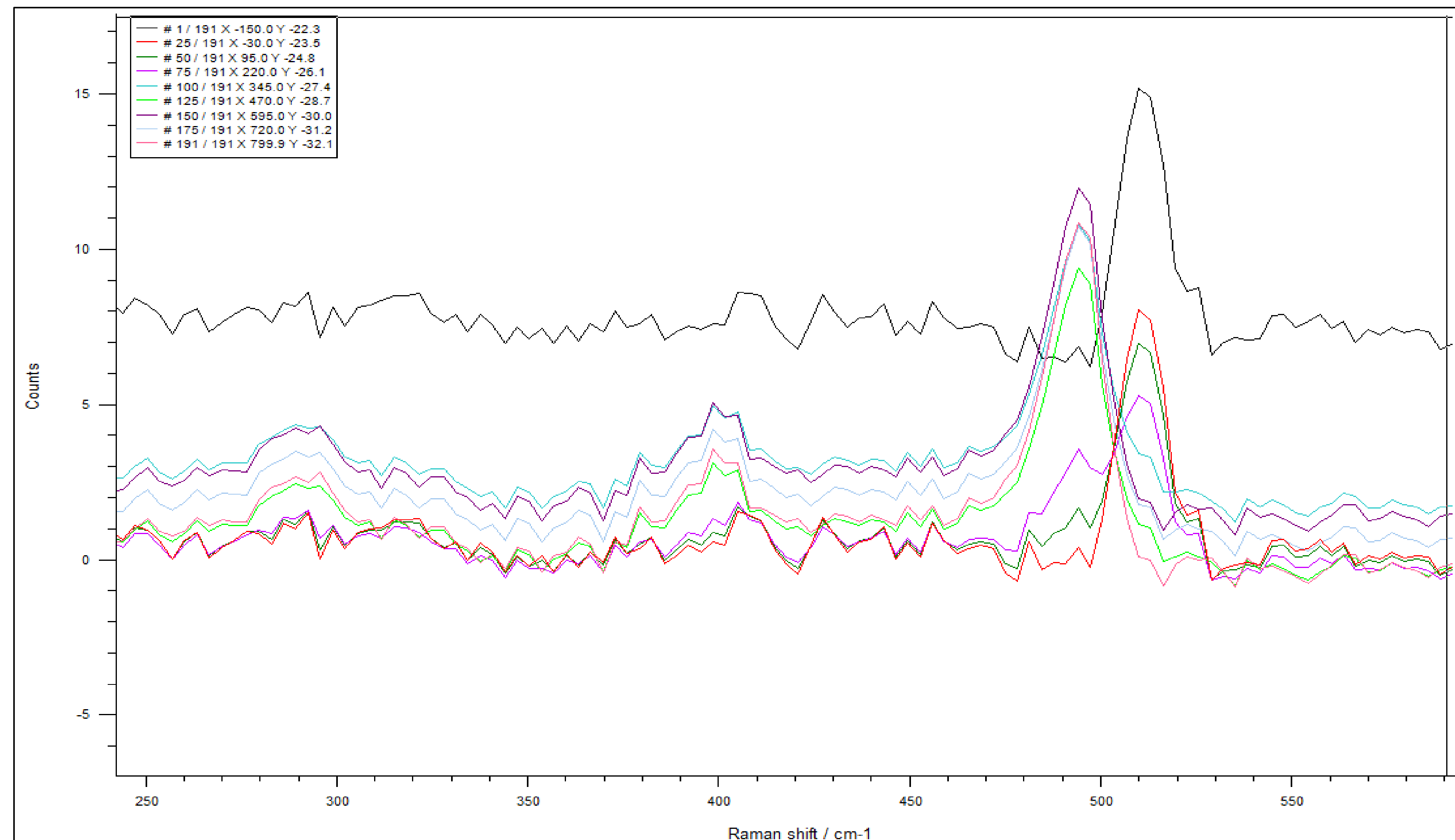
# Focus on Wf 05 COND2

- Process condition: Laser anneal 3x
- Measurement:
  - center square, streamLine1000 um, step 1 um, exposure time 1s
  - edge square, streamLine 900 um, step 5 um, exposure time 1s
  - crossline, streamLine 400 um, step 0.5 um, exposure time 1s
  - depth profile, step 0.1 um, exposure time 1s, Z center 1,9 um, Z edge 2,9 um



Evolution spectra from center to corner (UV laser):



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# Wf 05 COND2

## Depth profile (green laser only)

Only the intensity decreases with the increasing Z.

| | Peak position |
|---|---|
| Curve 1 edge | 294,238 |
| Curve 2 edge | 501,167 |
| Curve 3 edge | 401,934 |
| Curve 4 edge | 520,114 |
| Curve center | 519,437 |

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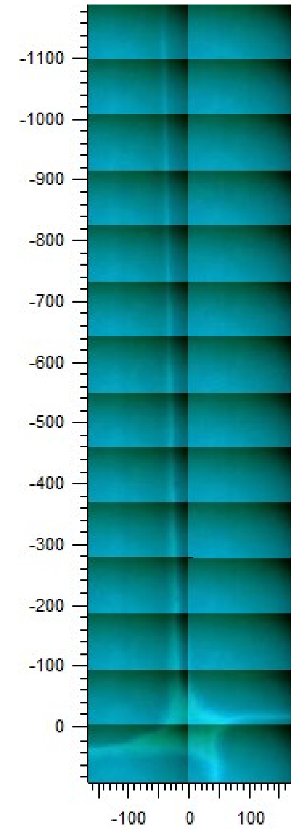
# Focus on Wf 05 COND3

- Process condition: Laser anneal 30x
- Measurement:
  - center square, streamLine1000 um, step 1 um, exposure time 1s
  - edge square, streamLine 900 um, step 5 um, exposure time 1s
  - crossline, streamLine 400 um, step 0.5 um, exposure time 1s – Near Corner (200 um UV/120 um Green) and Far Corner (2000 um UV/1200 um Green)
  - depth profile, step 0.1 um, exposure time 1s, Z center 1,9 um, Z edge 2,9 um




Evolution spectra from center to corner (UV laser):

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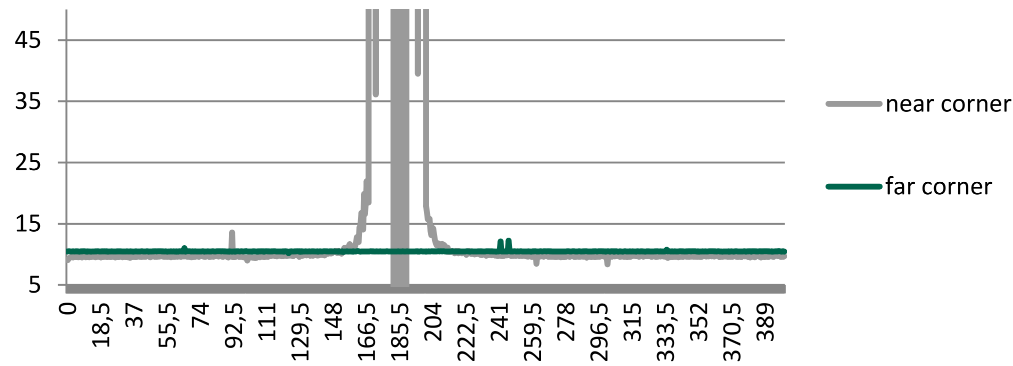
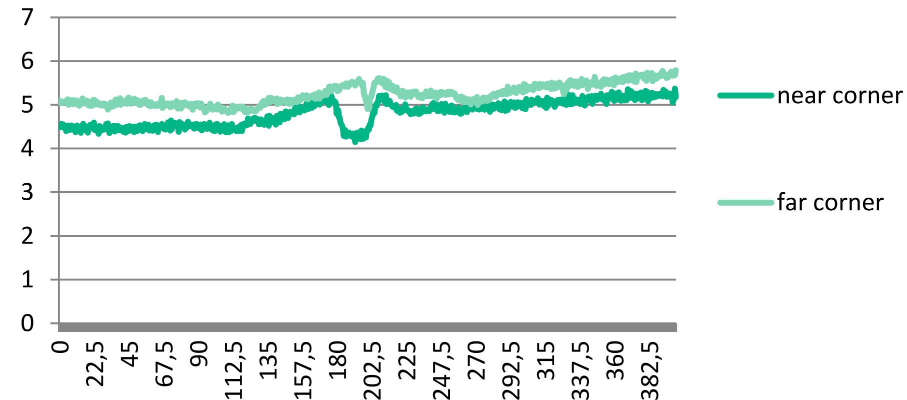
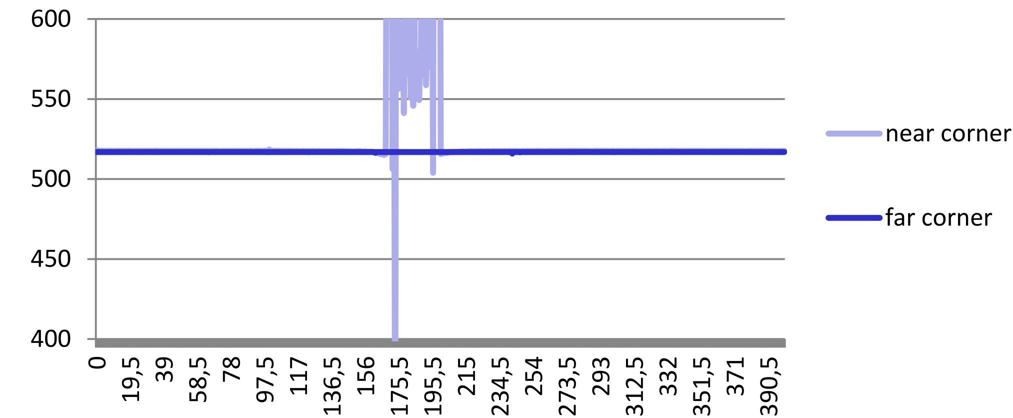
## Wf 05 COND3

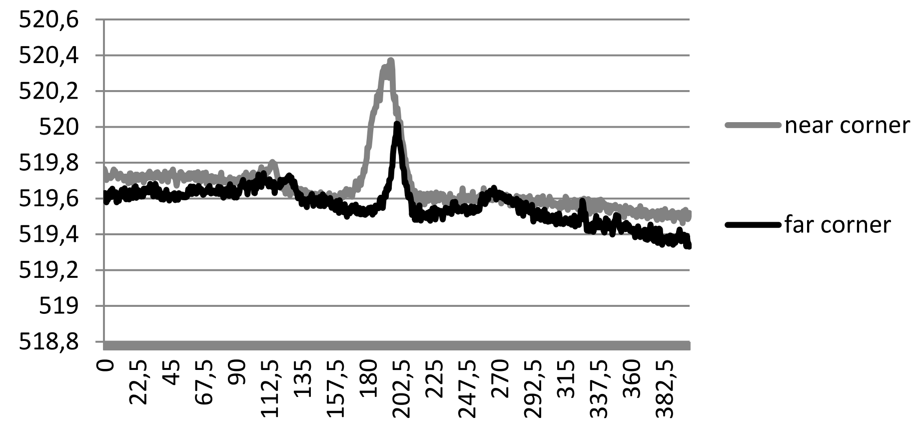
**Cross line**: In the UV crossline there are differences between the edge and the square only for near corner, in the Green spectra there are differences for both of the crosslines.

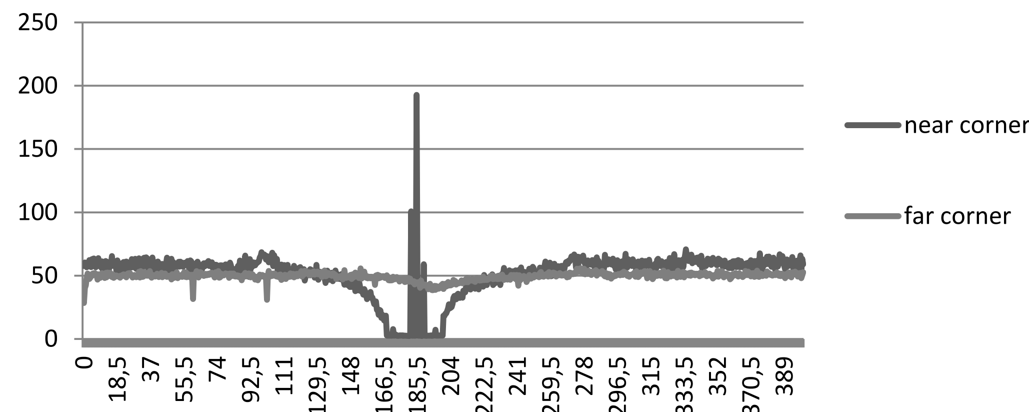


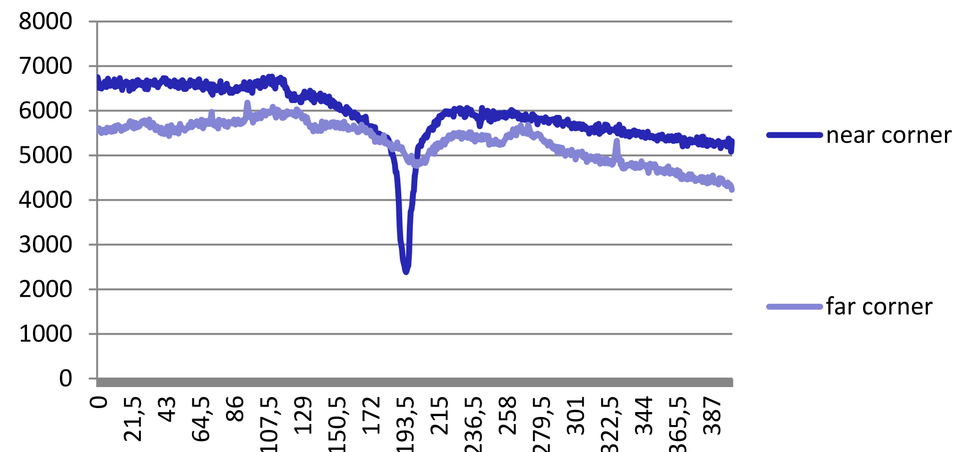




| | Peak Position | Height | Width |
|---|---|---|---|
| UV near | 517,908 | 57,5835 | 9,10453 |
| UV far | 516,896 | 34,0553 | 10,4628 |
| Green near | 520,106 | 4526,09 | 4,4084 |
| Green far | 519,614 | 5612,84 | 5,1018 |

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# Conclusions

- Using the green laser it’s possible to detect all of the four peaks of the structure like in the reference: the differences is due to the different process condition. In wf 02 there are all the four peaks in the center, due to the greater concentration of Ge and different thermal budget. On the laser annealed samples, at  the edge of the laser spot, the higher concentration of Ge is caught by the Raman and it’s due to reduced annealing and diffusion.
- Using the UV laser it’s possible to see the peak of Si-Si in SiGe: the strong shift of the peaks in the center measurement and in the edge measurement shows the big tensile strain in the structure, due to the presence of Ge. The UV laser is more sensitive to this shift instead of green laser because of the smaller penetration depth.
- The crystalline structure are well defined and it improves using more thermal power, like the narrower width shows.
- The edge and the center of the square in wf 05 shows differences in structure and phases.

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