# SiGe/Ge Surface Passivation by ALD

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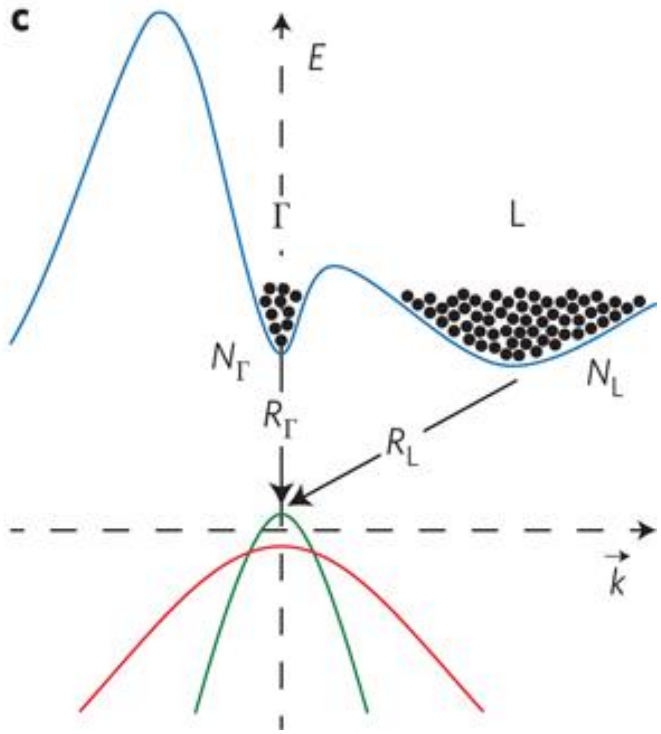
# Why is Ge Passivation so Hard?

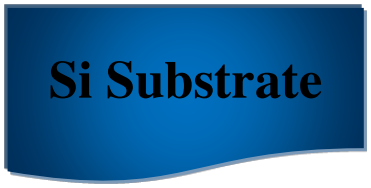
- There is no stable Ge oxide like $SiO_2$ to Si.
- Surface recombination provides a non-radiative pathway.
- Degradation of photoluminescense (PL) signal -> undesired for light emitting applications (LEDs / lasers).



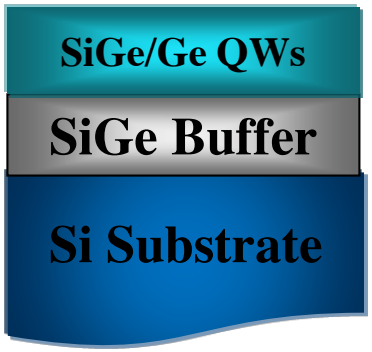
# Ge Oxidation

- 4 different oxidation states (1+, 2+, 3+, 4+)
- Affected by temperature, pressure, and methods
- $GeO_2$ passivates the surface and gives low Dit
- Unfortunately, it can be easily etched away by water (not stable!)
- How do we protect $GeO_2$ and relate low $D_{it}$ to higher PL signal?

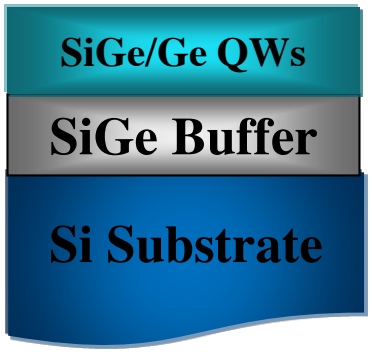
# Process Flow




1. Si wafer.

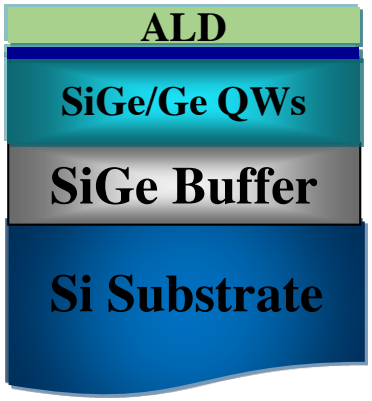



2. Epi growth.




3. HCl clean.


4. Thin ALD.




5. Oxidation

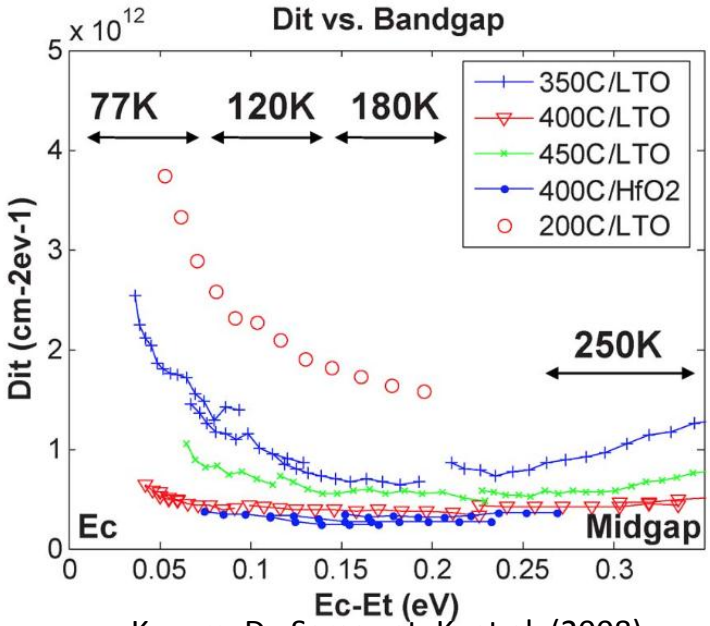

6. Thicker ALD for protection.


7. PL.

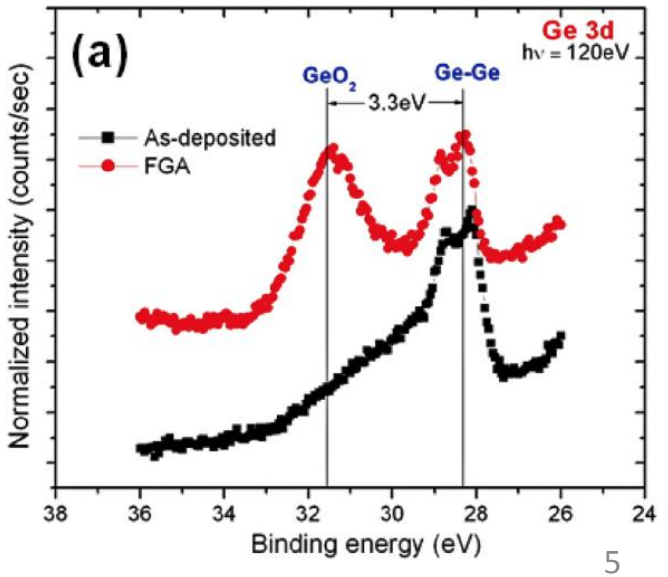
# Oxidation Methods

- Ozone oxidation
  - Ozone is more reactive than $O_2$.
  - 400 °C is required to achieve high oxidation state ($GeO_2$ instead of $GeO_x$).
  - Higher temperature causes transformation of oxide.
- Forming gas anneal
  - Transient formation of water.
  - Water reoxidize the substrate surface.

Both methods can be done in the ALD system!




Kuzum, D., Saraswat, K, et al. (2008)




Swaminathan, S., McIntyre, P, et al. (2011)

# Design Parameters

- What ALD layer?
  - $Al_2O_3$ or $HfO_2$
- Precursors of ALD?
  - $H_2O$ (thermal) or $O_2$ plasma
- First layer thickness?
  - 1 nm or 2 nm.
- Oxidation methods?
  - Forming gas anneal or ozone
- Optimize the recipe (oxidation time, pressure…) for two different oxidation methods before varying the parameters above.

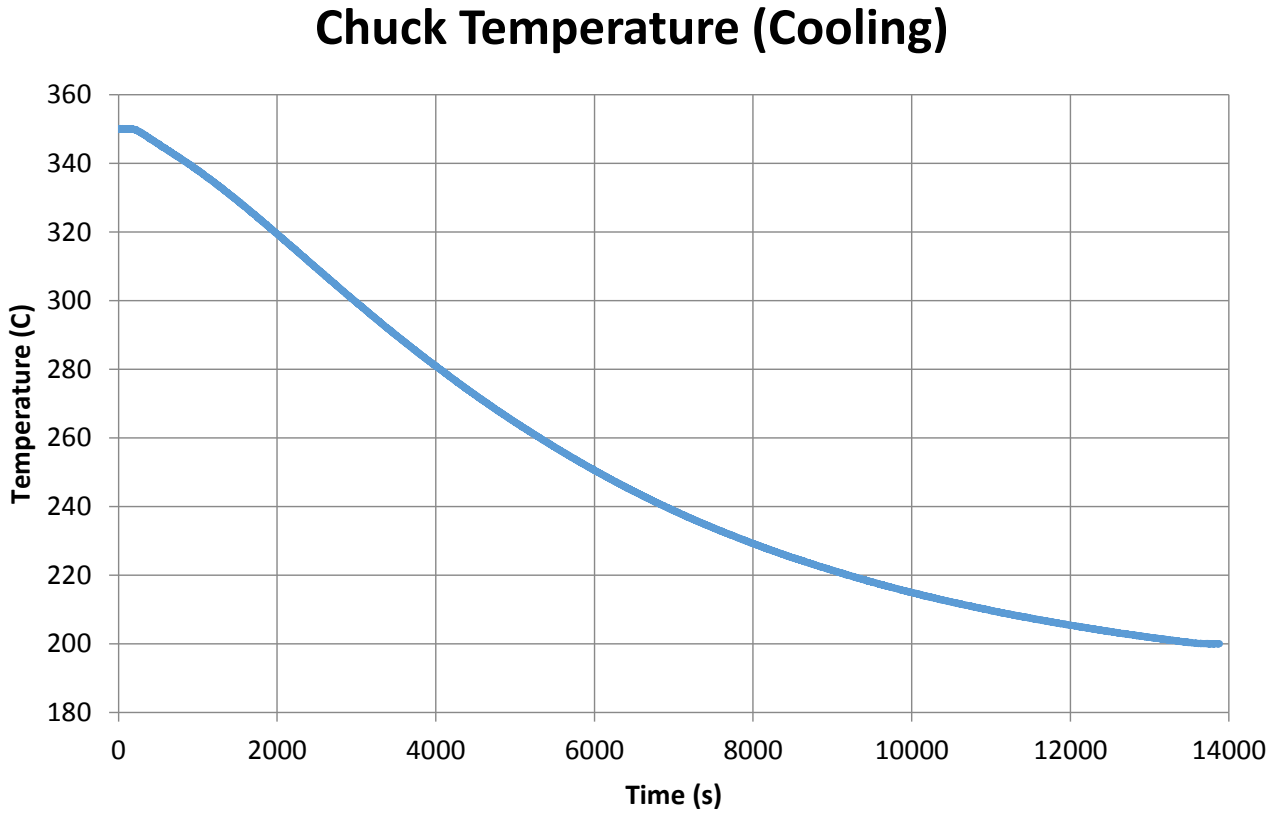
# DOE ($Al_2O_3$)

| # | Precursors (O2 plasma/H2O) | Oxidation Methods (O3/FG) | 1st layer thickness (1 nm/2 nm) |
|---|---|---|---|
| 1 | O2 plasma | O3 | 1 nm |
| 2 | O2 plasma | FG | 1 nm |
| 3 | O2 plasma | O3 | 2 nm |
| 4 | O2 plasma | FG | 2 nm |
| 5 | H2O | O3 | 1 nm |
| 6 | H2O | FG | 1 nm |
| 7 | H2O | O3 | 2 nm |
| 8 | H2O | FG | 2 nm |

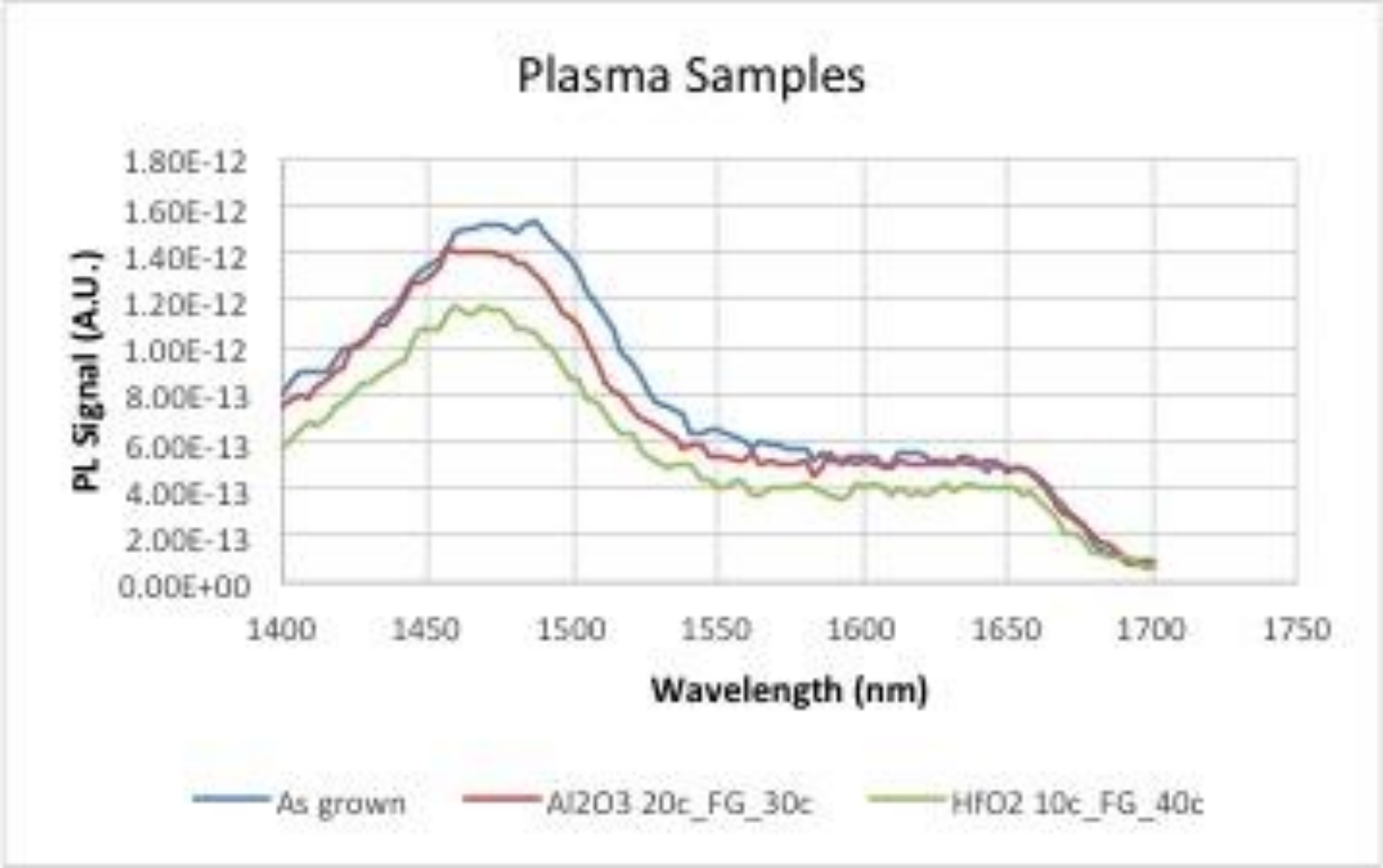
For #9~#18, repeat the same runs for $HfO_2$

# Heating & Cooling

- ALD growth at 200 ˚C but oxidation at 350 ˚C or 400 ˚C.
- 4 heaters: Reactor heater 1&2, Chuck & Cone
- ~30 min for all heaters to go from 200 ˚C to 300 ˚C.
- Chuck heats up the fastest and cools down the slowest (3.8 hrs for 350 ˚C to 200 ˚C).

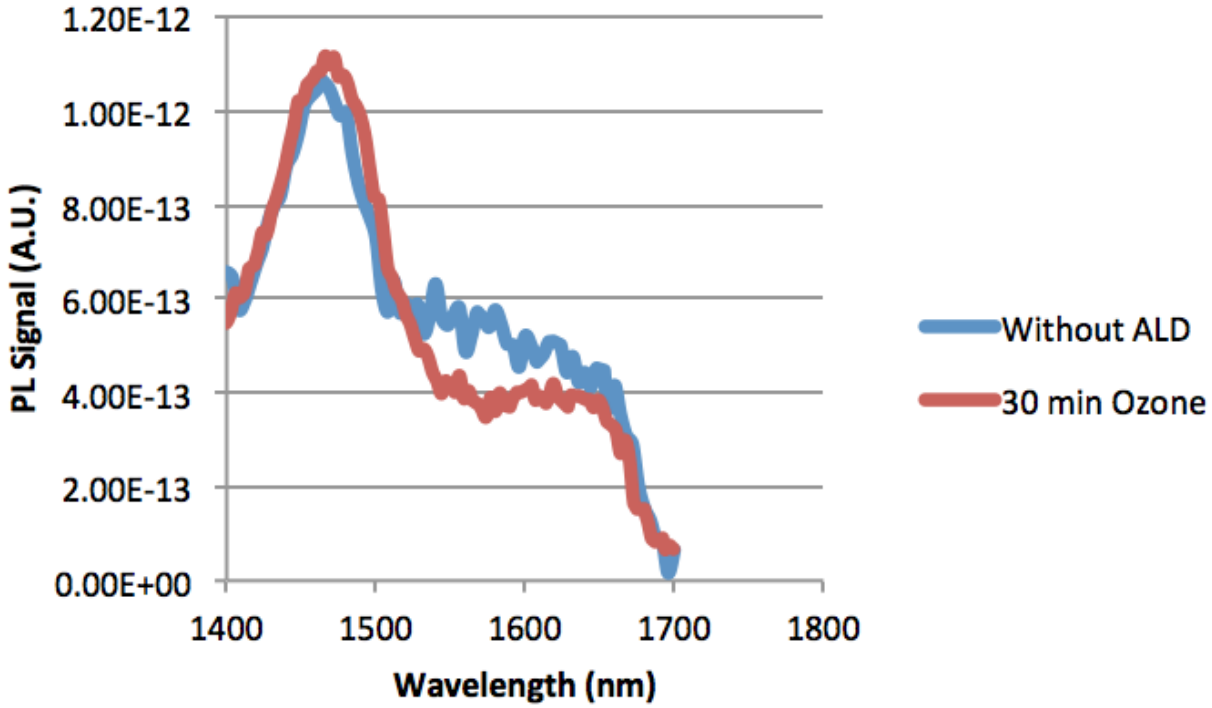


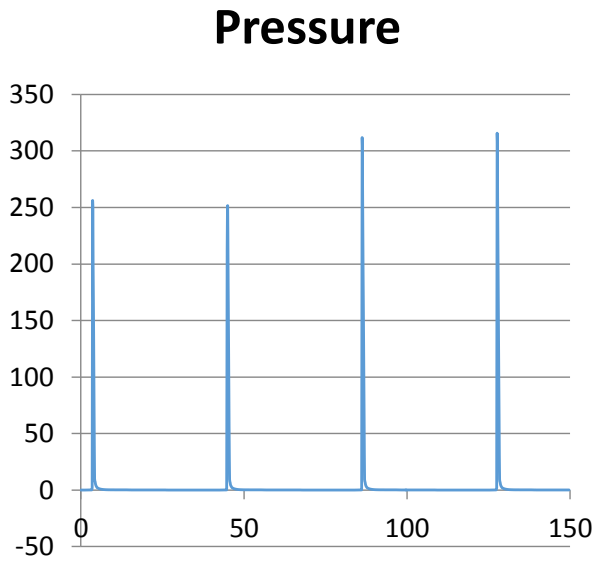
# Plasma Samples w/ FG




- Degradation of PL signals.
- Plasma strikes the surface and causes damages. Matches with past results where plasma ALD results in a higher $D_{it}$.

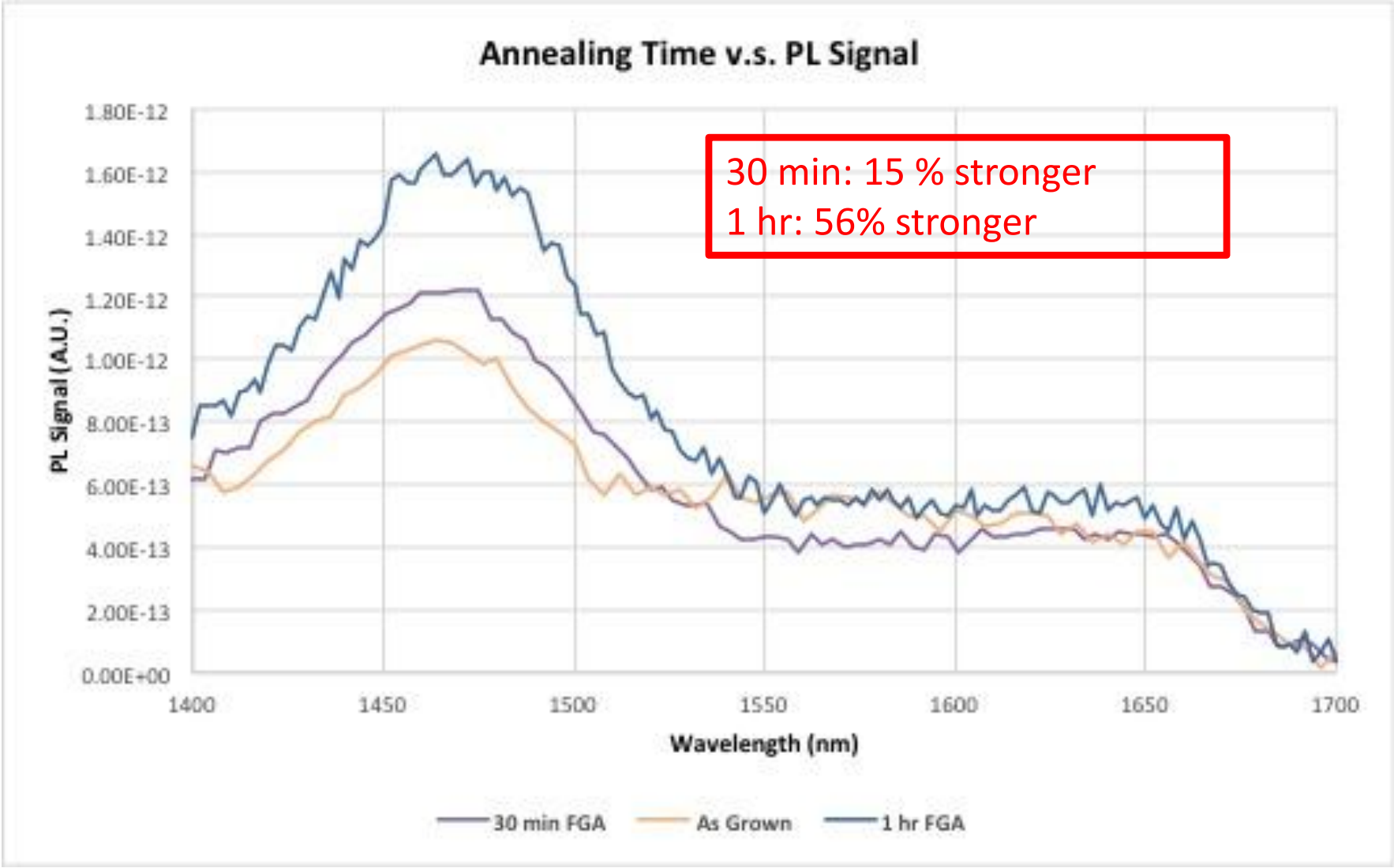
# Thermal $Al_2O_3$ w/ Ozone



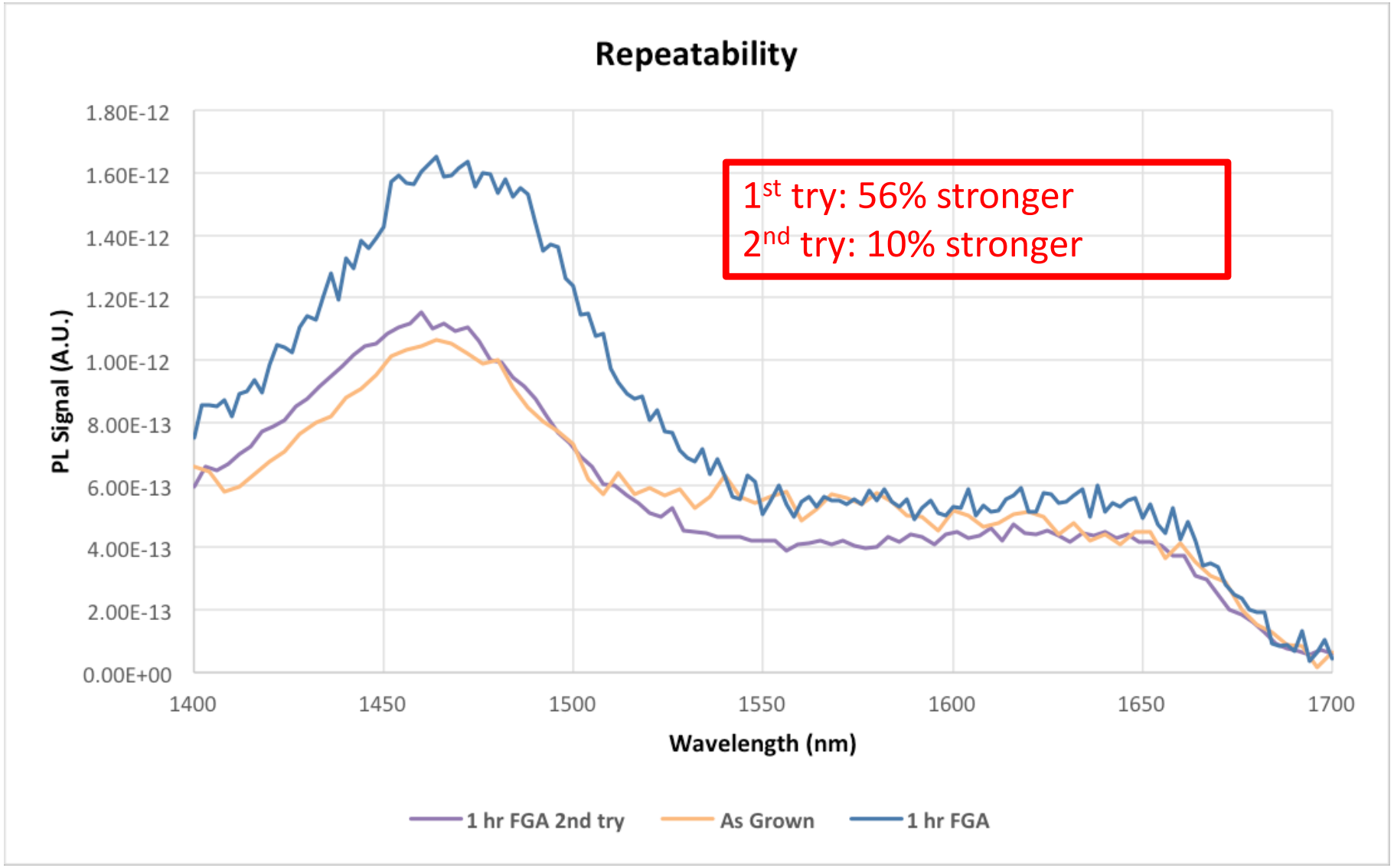

- Not a constant flow of ozone: pulse ozone into the chamber, close the valve, wait for it to react, and open the valve.
- Half of ozone decompose to oxygen at 250 °C in one second. Decompose even faster at 400 °C!

# Thermal $Al_2O_3$ w/ FG

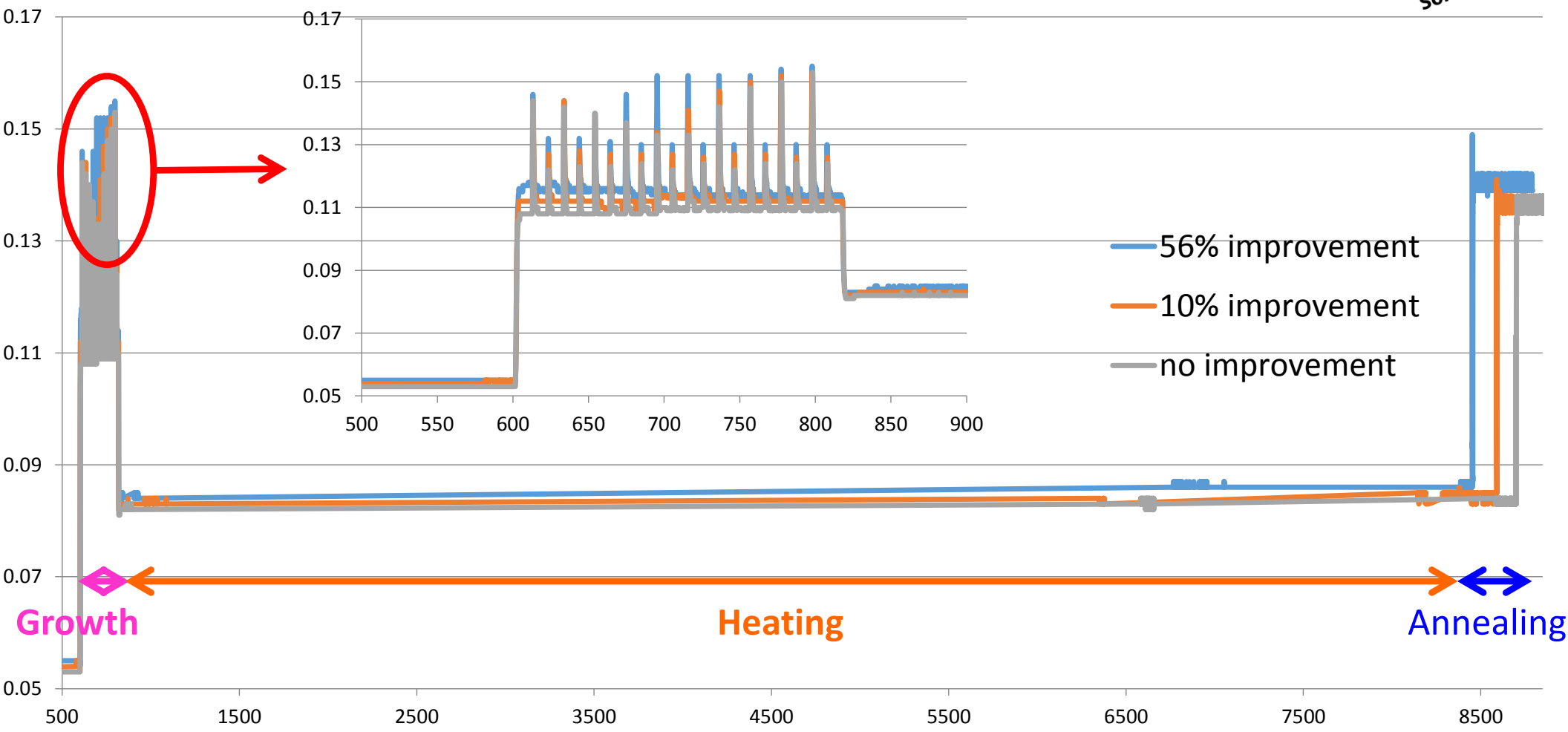



- We obtained a clear improvement of PL signal after ALD treatment.

# Not able to repeat 56%..

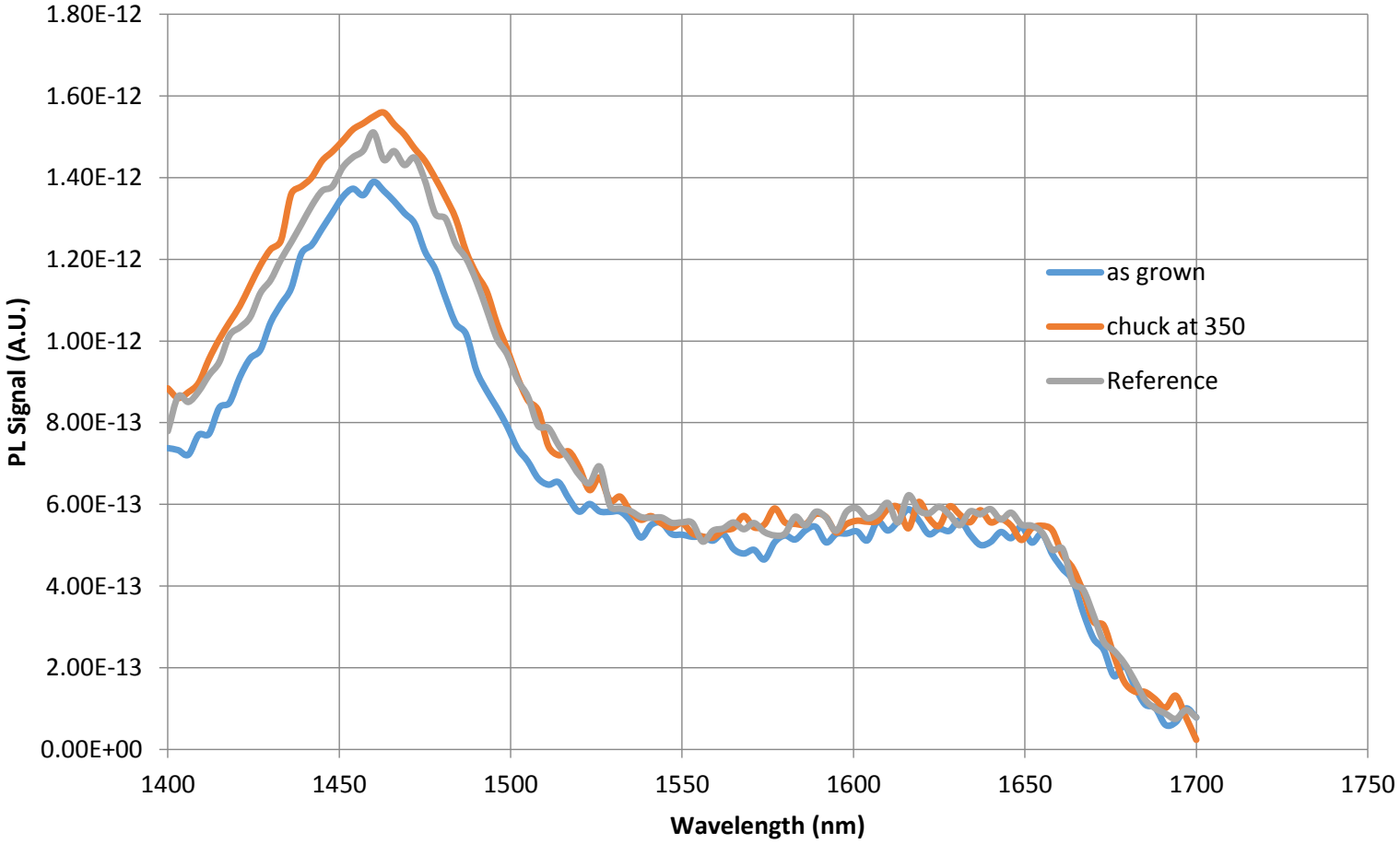


# What makes the difference?



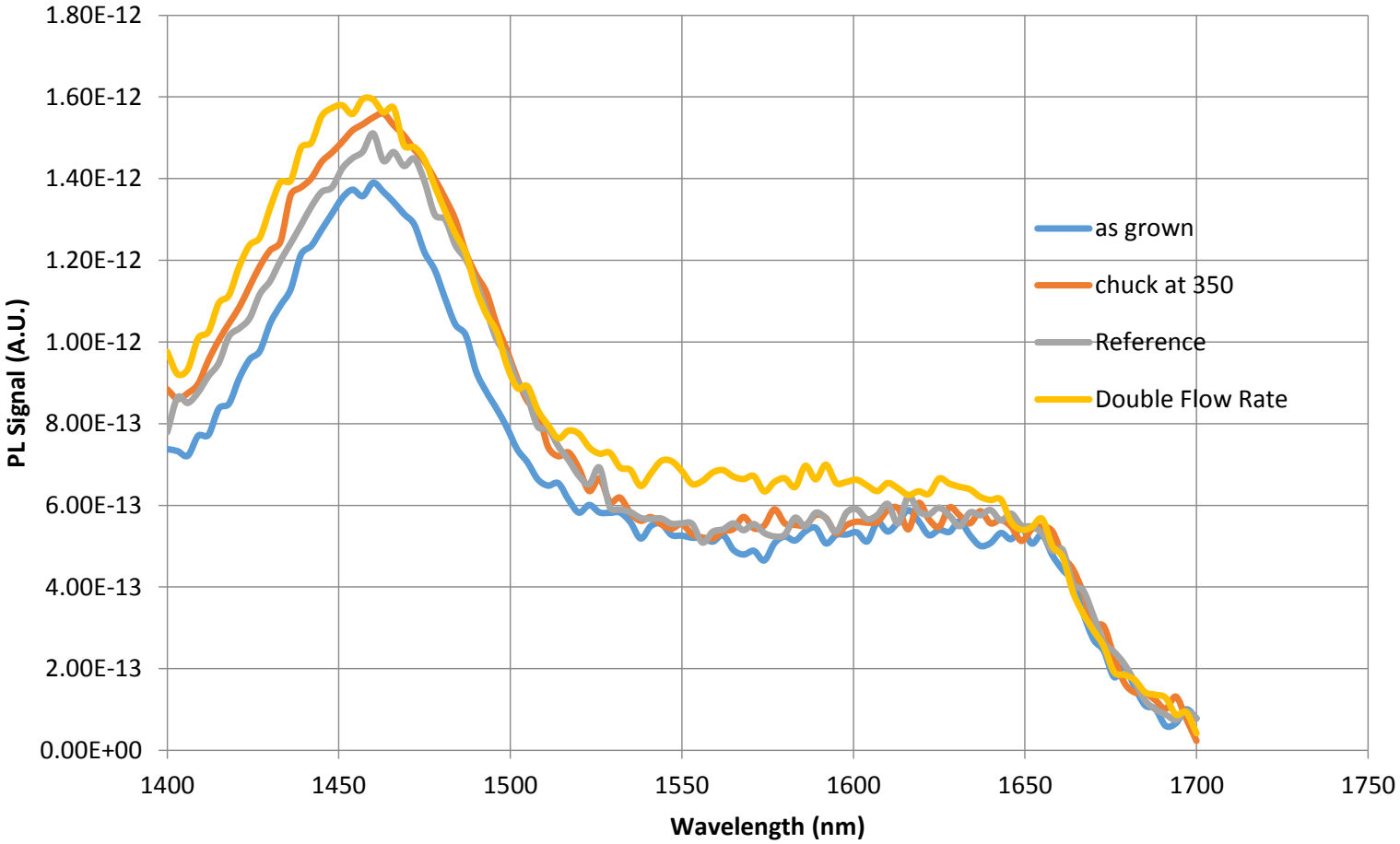

- Shorter heating time (sample exposed to remaining water vapor) gives better results?
- Higher pressure gives better results?

# Debugging…



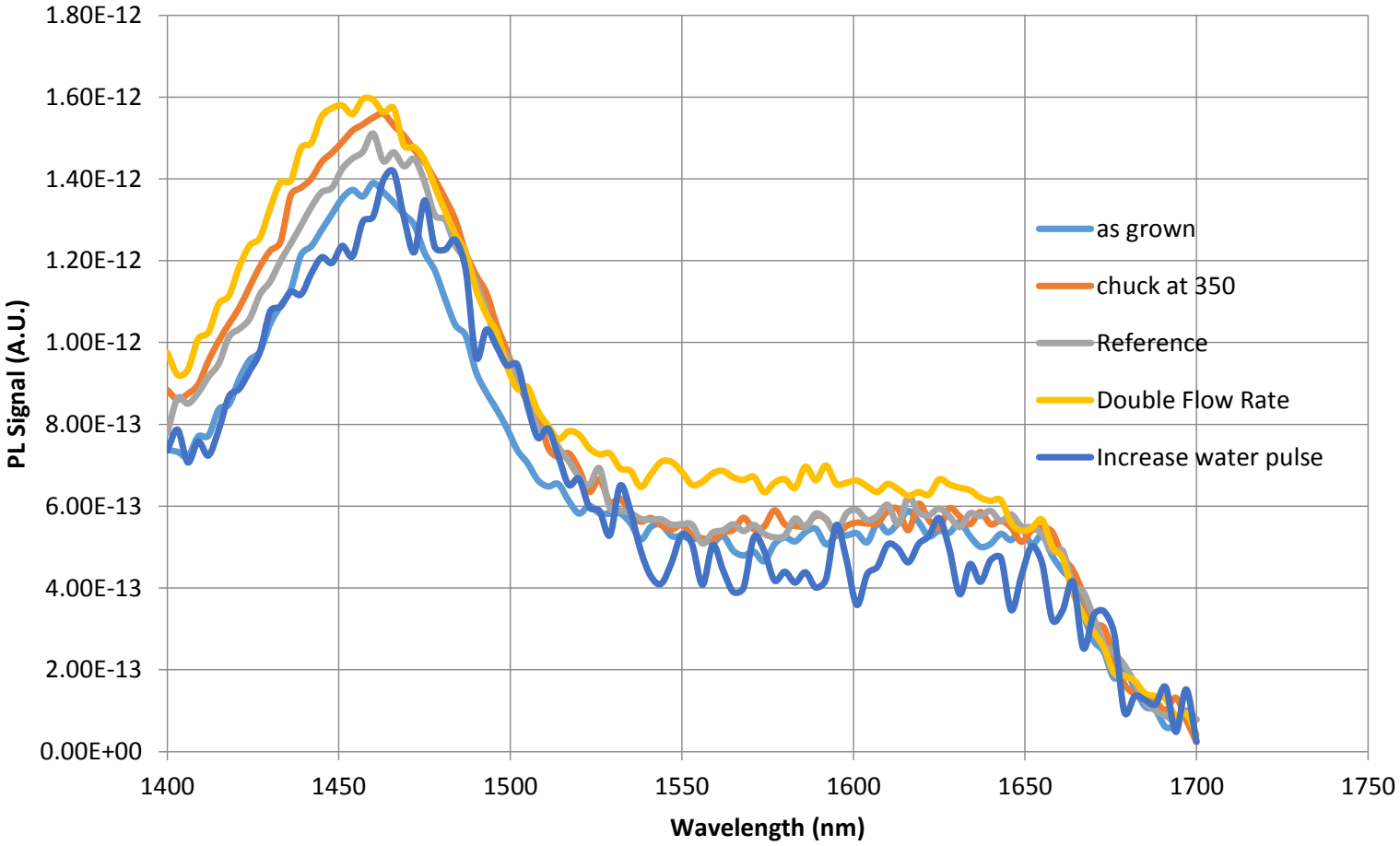

- Shorten heating time by setting ambience at a lower temp: 12%.

# Debugging…



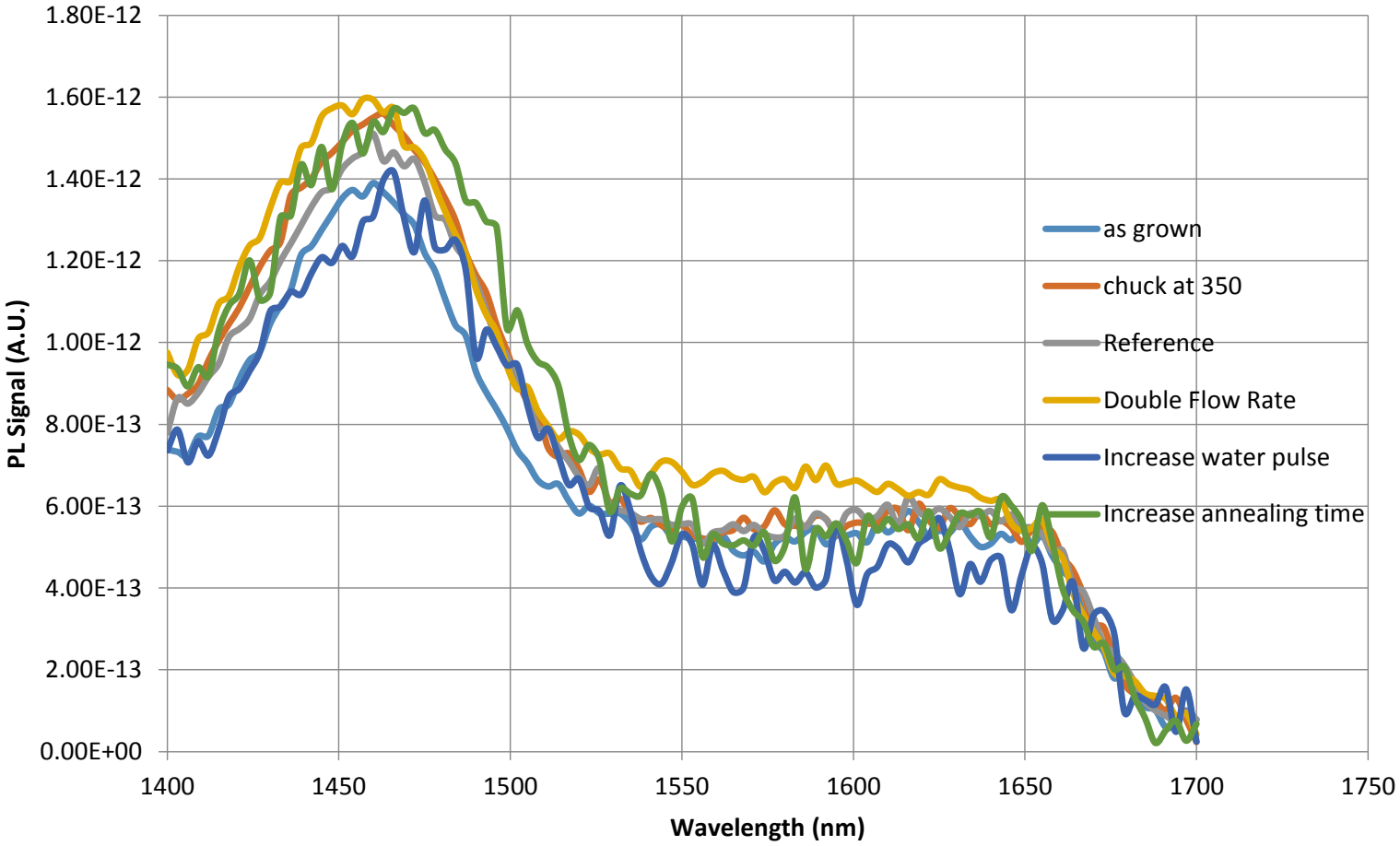

- Shorten heating time by setting ambience at a lower temp: 12%.
- Double the flow rate of forming gas: 15%.

# Debugging…




- Shorten heating time by setting ambience at a lower temp: 12%.
- Double the flow rate of forming gas: 15%.
- Increase water pulse during ALD growth: 0%.

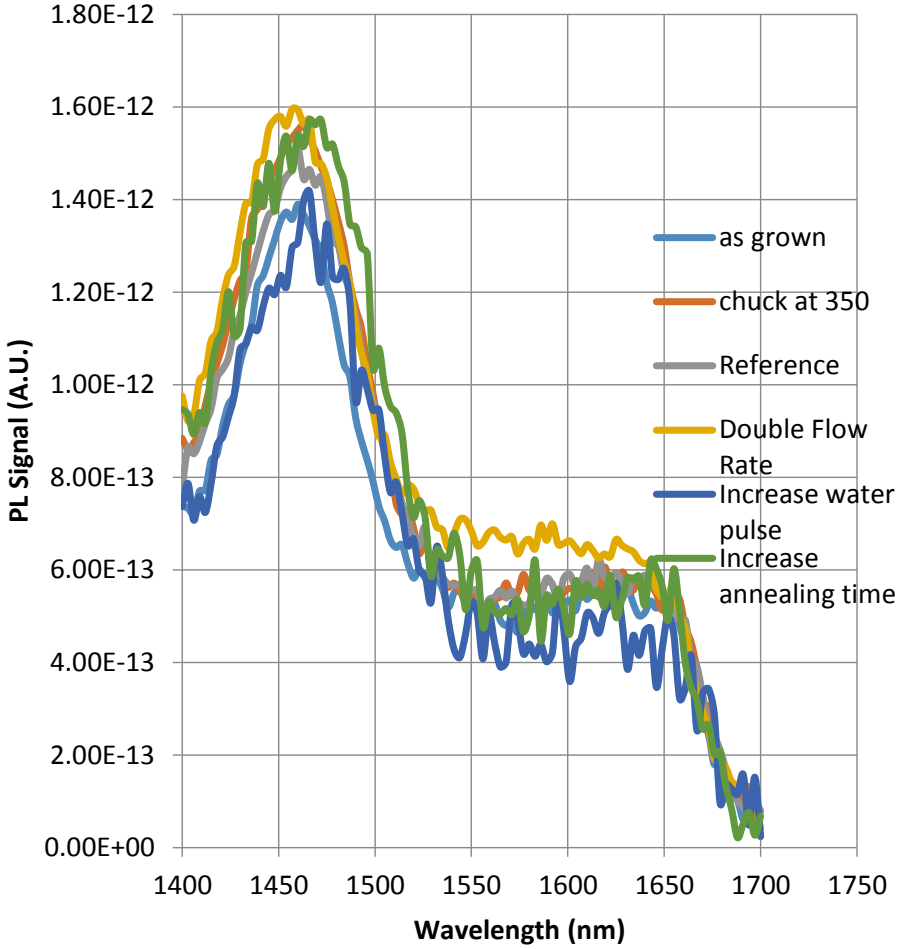
# Debugging…




- Shorten heating time by setting ambience at a lower temp: 12%.
- Double the flow rate of forming gas: 15%.
- Increase water pulse during ALD growth: 0%.
- Increase annealing time: 15%.

# Key Observations

- Doubling flow rate increases pressure from 0.14 to 0.20 Torr. It has little effect on passivation.
  - Adjust the valve opening to have a larger change in pressure.
- Increasing the annealing time from 1 hour to 1.5 hour improves the signal by a negligible amount.
- Increasing water pulse may etch away $GeO_2$ formed during FGA and degrades the improvement.



# Conclusions

- Demonstrated a repeatable 15% improvement on PL signal by forming gas anneal.
- Ozone capability of Fiji3 was first brought up.

# Future Work

- Finish the DOE with the best recipe we have to understand how different ALD material and different 1st layer thickness affect the passivation.
- Study the degradation of signal over time with different cap layer thickness.
- Try $O_3$ as the precursor for ALD layer. This might prevent water to etch away the grown $GeO_2$ during the 2nd ALD layer growth.
- Apply the passivation method to microdisk resonator.

# Questions?