

Thermal conductance of zigzag graphene nano-mesh

Advanced Research Laboratory, Anritsu Corporation

Takamoto Yokosawa, Masahiro Kamada, Taisuke Ochi, Tomohiro Matsui

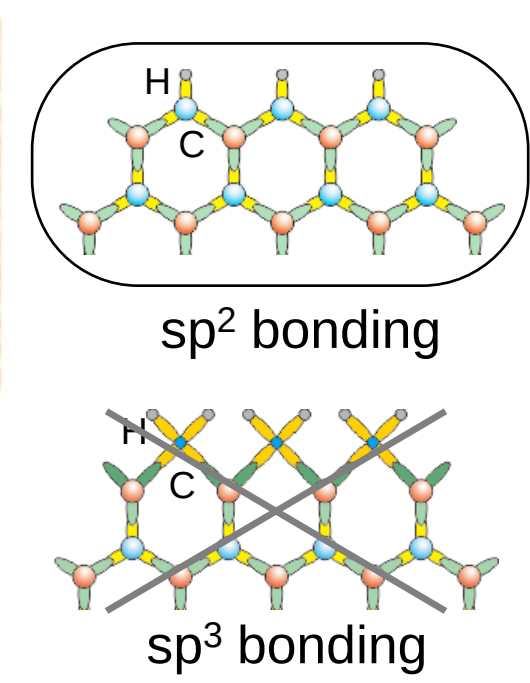
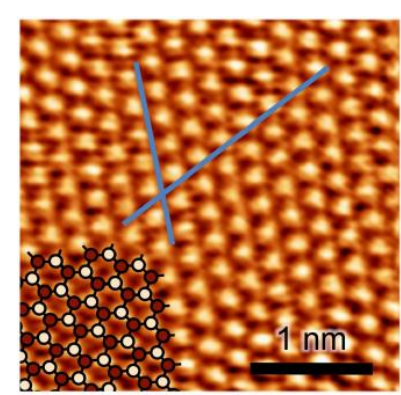
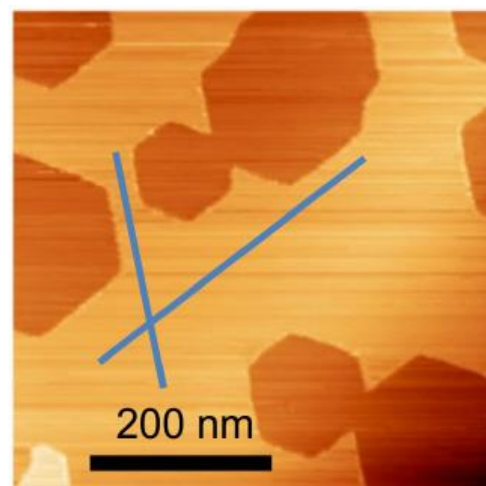
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Introduction

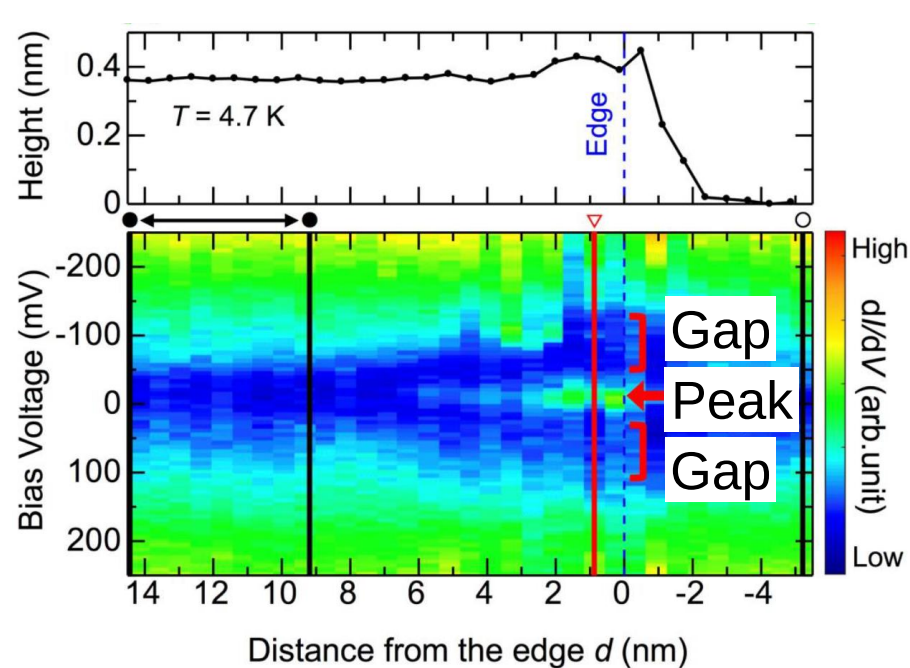
Zigzag edge by H-plasma etching

Hexagonal nanopits are fabricated by **Hydrogen(H)-plasma etching** [1]

The nanopit edge is **Zigzag** structure, which is:



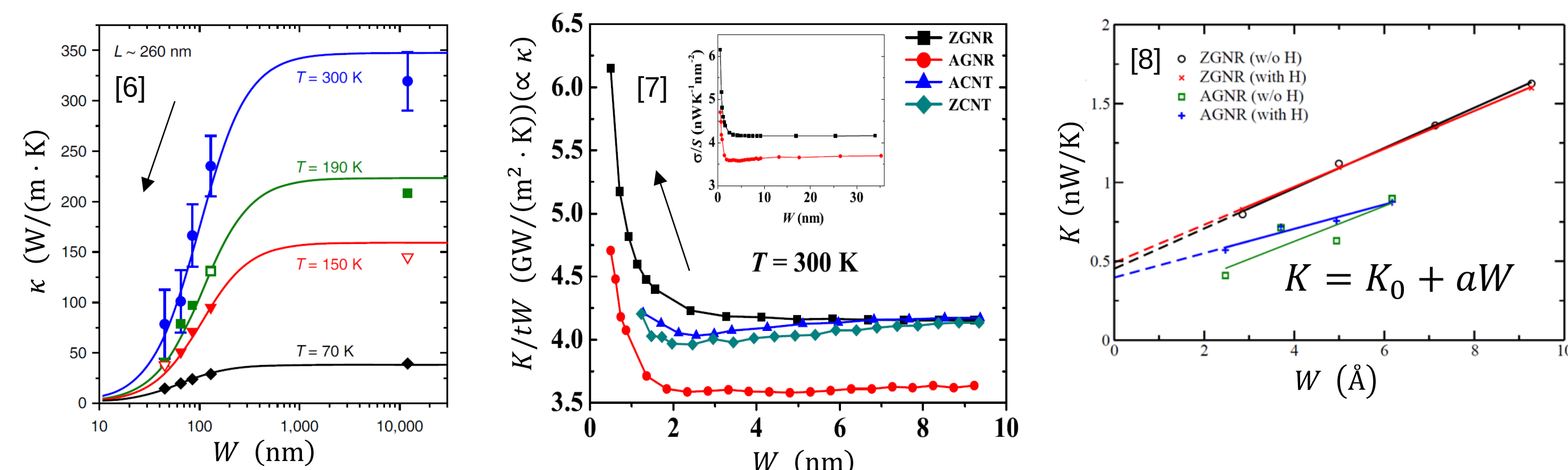
- **Atomically precise**
← confirmed by STM/S [2]
- **Terminated by only one H atom**
(sp² bonding is kept to the edge)
← confirmed by HREELS [3]



Localized electronic state at Fermi energy

Spin polarized zigzag edge state is expected [4] and confirmed by STM/S [5]

Thermal conductivity of Graphene nanoribbons (GNRs)



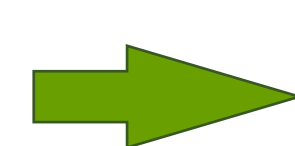
In general, **the thermal conductivity κ decreases by decreasing nanoribbon width W** . (transport mechanism also changes from ballistic to diffusive.)

Some theoretical studies suggest, **the κ increases for narrow GNR**.

A study suggests, the thermal conductance K ($= \frac{W \cdot t}{L} \kappa$) is expressed as $K = K_0 + aW$ (linear W dependence with an offset).

Motivation

In most experiments, the edge shapes are not controlled in atomic scale.

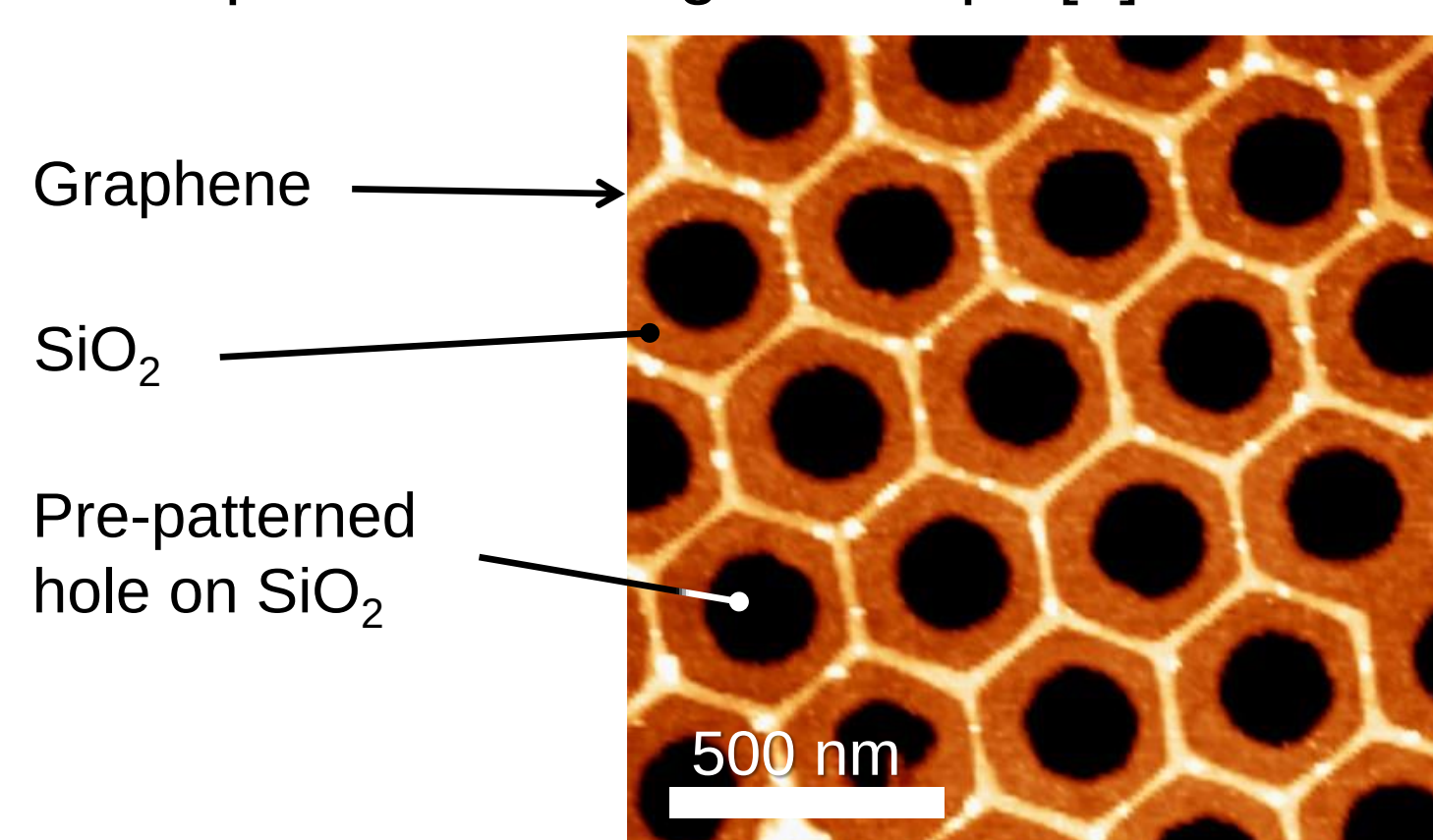


How about the thermal conductivity κ of GNR with zigzag edges (zGNR) and the network of zGNR (zGNM).

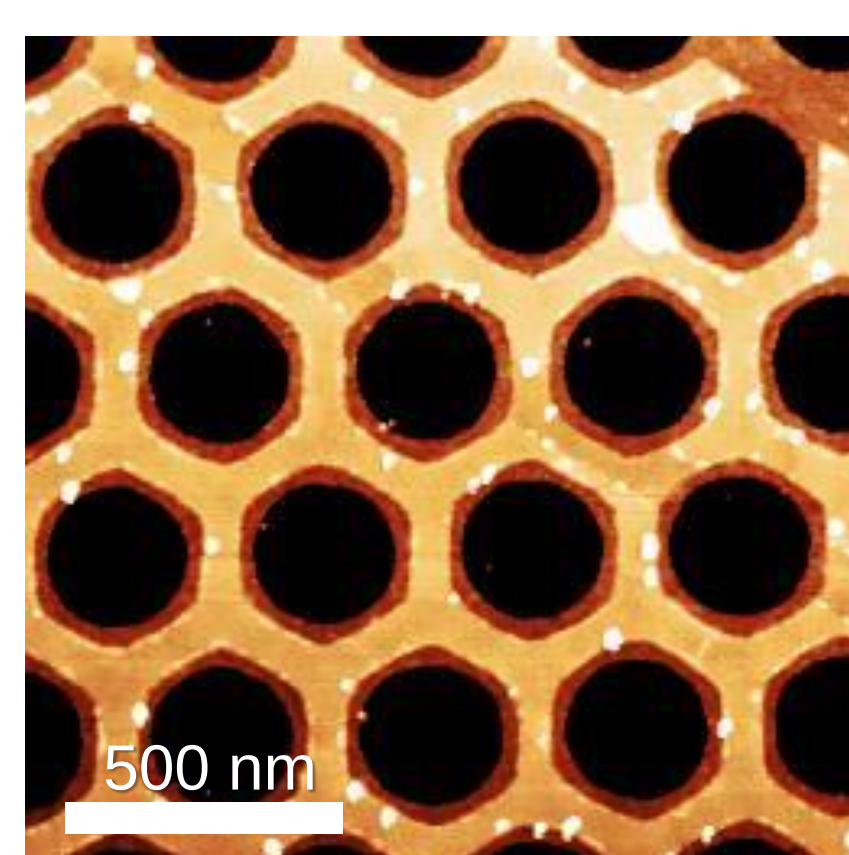
Experimental

Zigzag Graphene Nanomesh (zGNM)

zGNMs with various nanoribbon width W are fabricated applying the H-plasma etching technique[9].



$W \sim 20 \text{ nm}$ ($\sim t \cdot 2.9 \text{ nm}$)



$W \sim 75 \text{ nm}$ ($\sim t \cdot 2.6 \text{ nm}$)

Zigzag direction can be the shortest pass from the heat spot to the electrode, which works as the heat bath.
→ effective length of the heat flow:

$$L_{\text{eff}} = \frac{L/2}{\sin \theta} \cdot \frac{2}{\sqrt{3}}$$

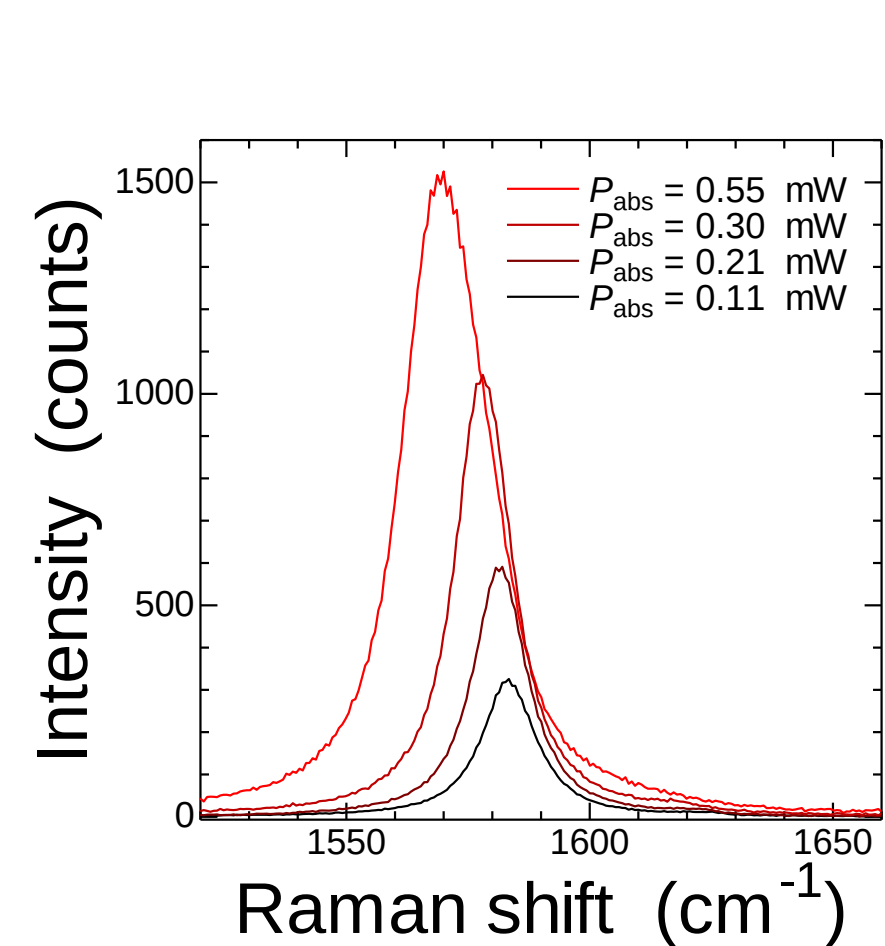
Raman laser spot : $\phi 400 \text{ nm}$

Method

The thermal conductivity κ of the zGNMs are obtained by analyzing the G-band position ω_G of graphene in **Raman spectroscopy**.

- The G-band shift $\Delta\omega_G$ is proportional to the graphene temperature shift ΔT .
 $\Delta\omega_G = \chi \Delta T$ ($\chi \cong -1.6 \times 10^{-2} \text{ cm}^{-1}/\text{K}$ [10, 11])
- Graphene is heated by the incident Raman laser.

Laser power absorbed by graphene: $P_{\text{abs}} \cong P_D (1 - \exp(-\alpha_{\text{ML}} N)) \cdot S$



P_D : laser power measured beneath the objective lens
 $\alpha_{\text{ML}} \cong 3.4 \%$: absorption coefficient of monolayer graphene
 N : number of layers
 $S = 1 - (1 - W/a)^2$: area fraction of the graphene region

$$\Delta\omega_G = \frac{1}{K} \chi P_{\text{abs}} \quad K : \text{Thermal conductance}$$

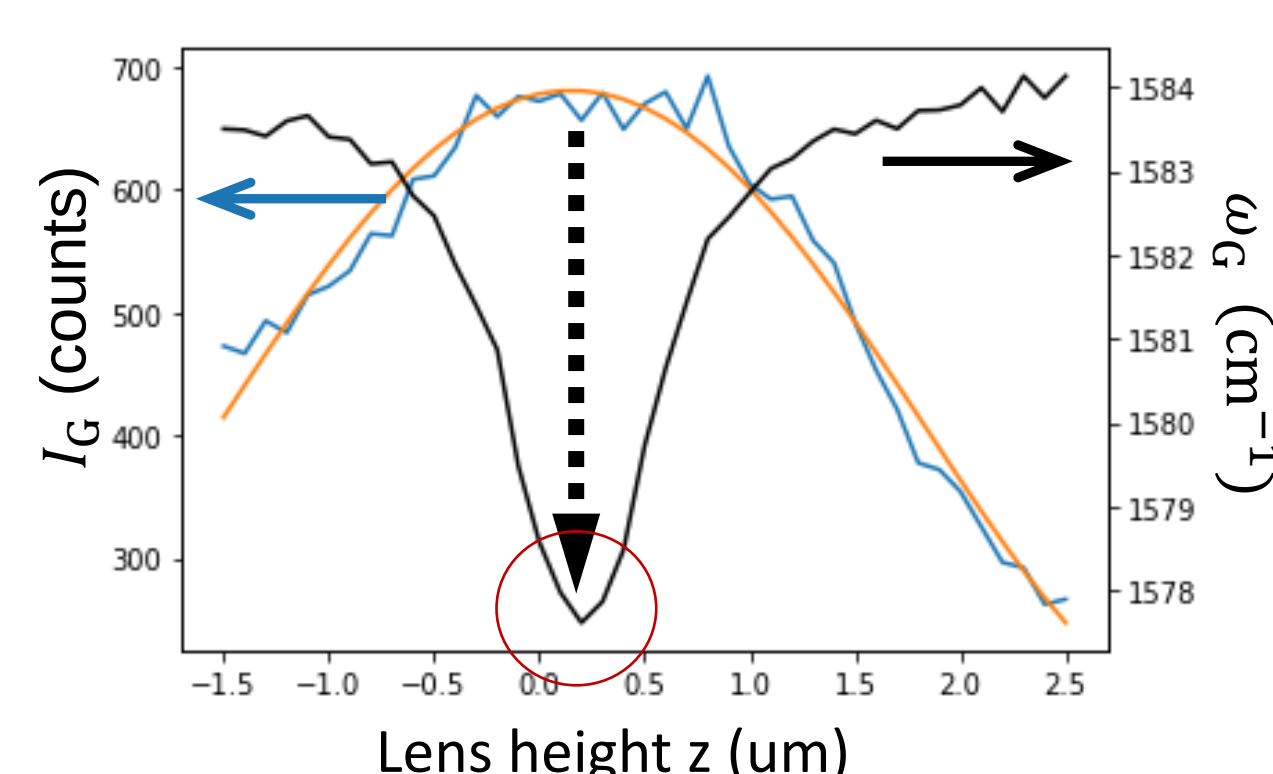
$$\kappa = \frac{L_{\text{eff}}}{W \cdot t} K \quad \kappa : \text{Thermal conductivity}$$

Raman spectroscopy

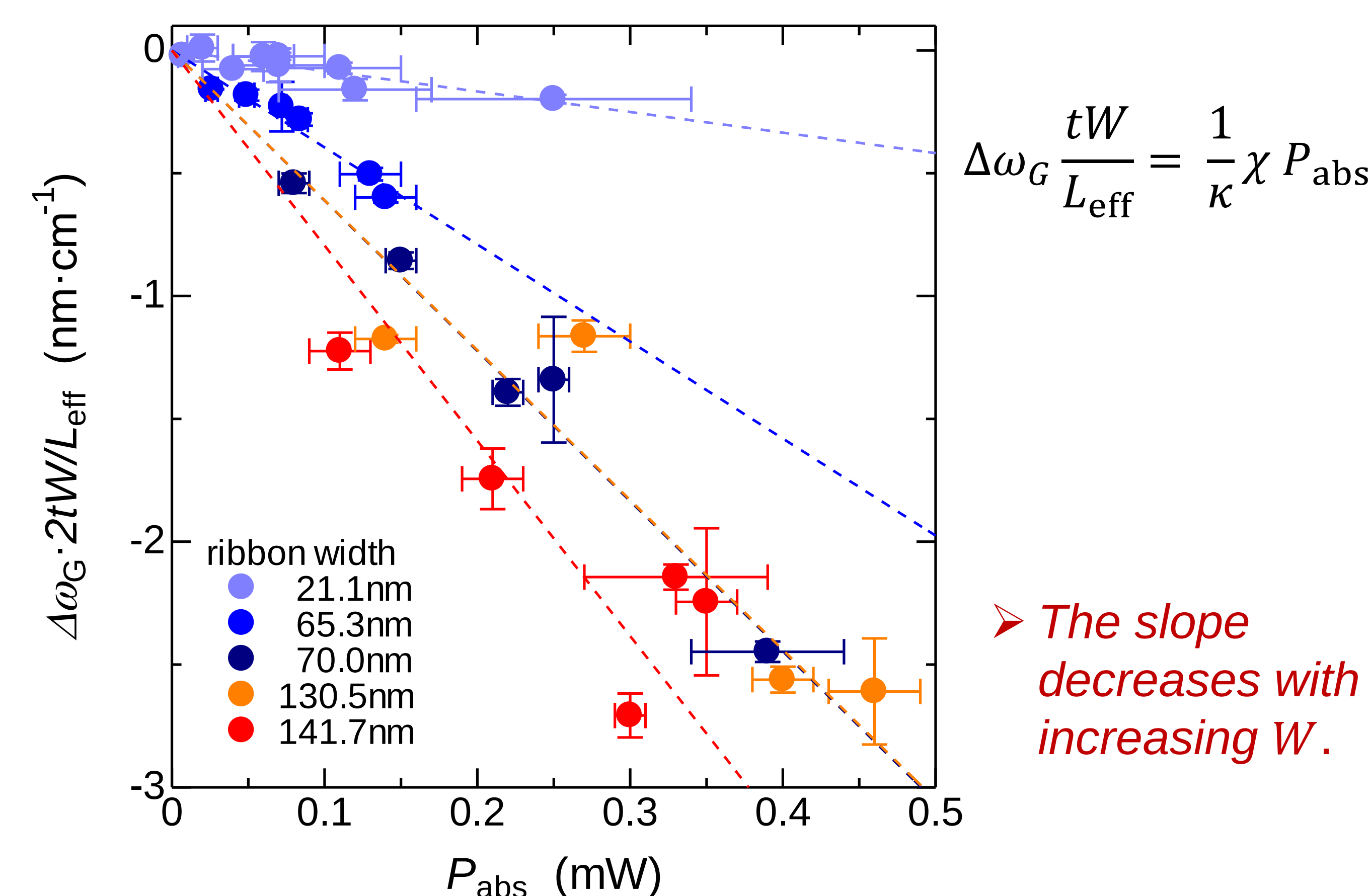
[Laser wavelength: $\lambda = 532 \text{ nm}$
Laser spot size: $\phi \sim 400 \text{ nm}$]

- To measure the value when the laser is focused on graphene
→ Raman spectroscopy by changing the lens height (z sweep)
- To minimize the heat load
→ keep the laser exposure time short
- To earn the S/N ratio
→ repeat z sweep measurement

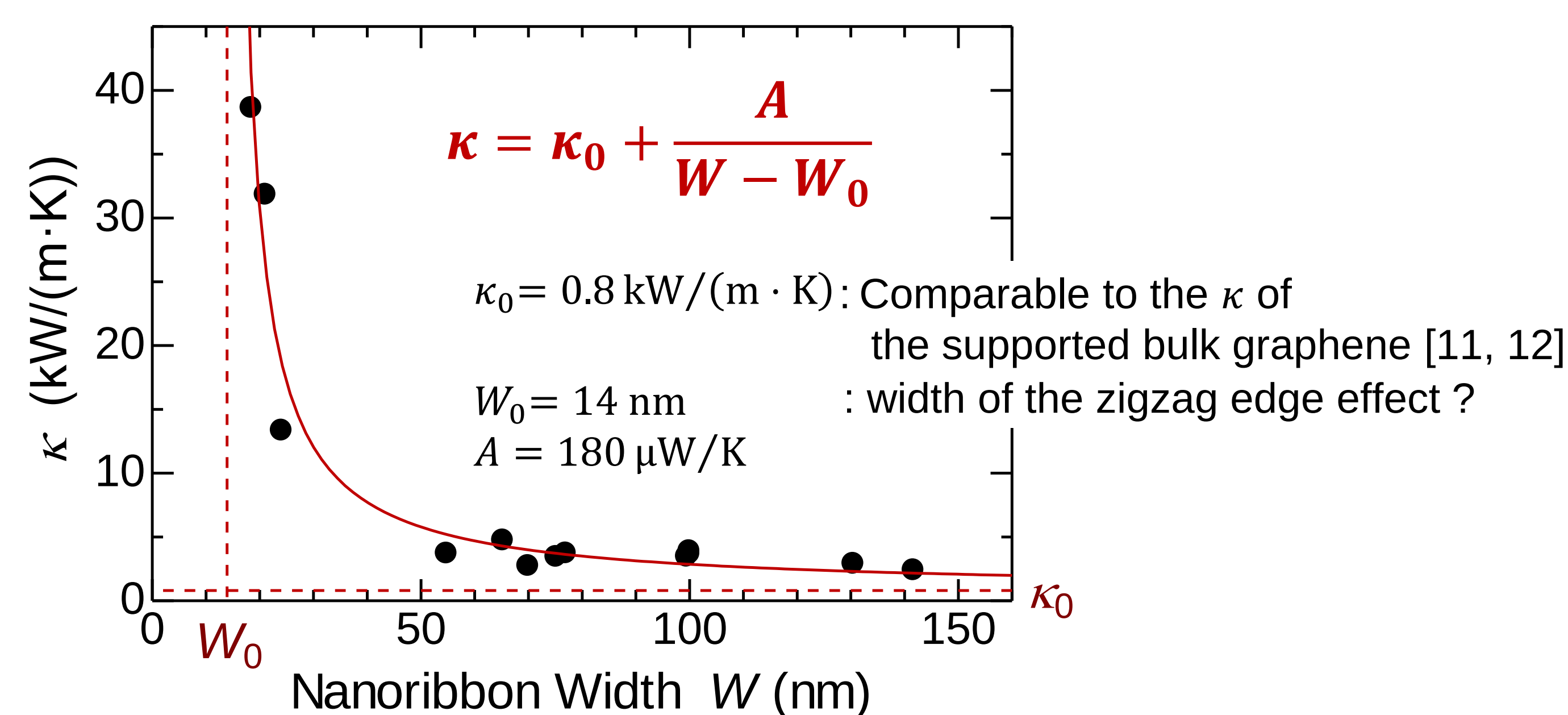
When the laser is focused on graphene,
→ G-band intensity I_G takes its maximum.
→ ω_G at that z should be the "real" value.



Result & Discussion



➤ **The slope decreases with increasing W .**



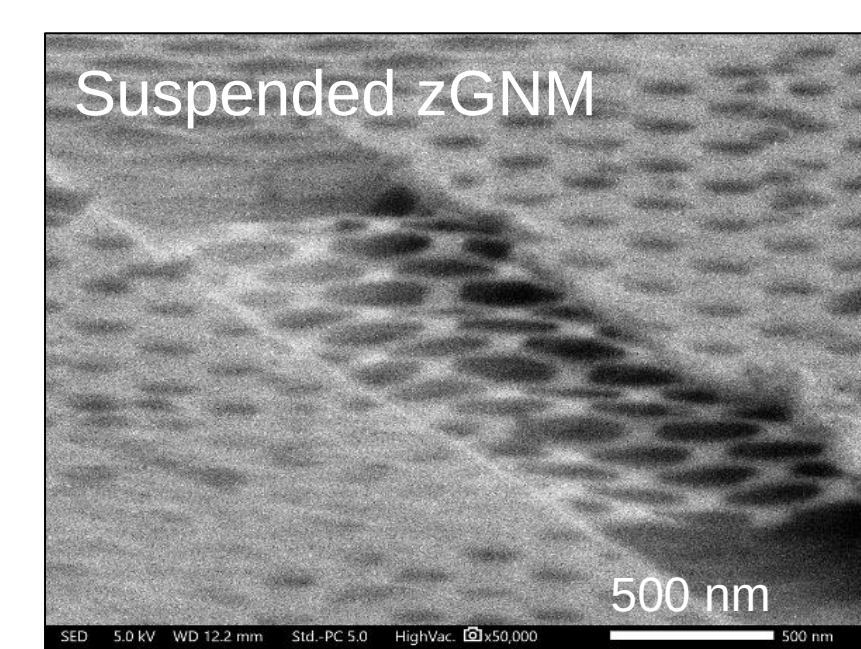
➤ **The thermal conductivity κ is drastically increased by decreasing the W .**

➤ The W dependence is well fitted by $1/W$.

Detailed theoretical study is desired.

Summary and Future prospect

- zGNMs with various nanoribbon widths are fabricated by H-plasma etching, and their thermal conductivities are evaluated by Raman spectroscopy.
- The **thermal conductivity of zGNM is significantly increased** by decreasing the nanoribbon width.
- In future, the effect of the **substrate** and the **geometry** should be studied, such as for the suspended zGNMs and the zGNRs.



Reference

- [1] T. Matsui *et al.*, J. Phys. Chem. C **123**, 22665 (2019).
- [2] AEB. Amend *et al.*, e-J. Surf. Sci. Nanotechnol. **16**, 72 (2018).
- [3] T. Ochi *et al.*, Carbon **203**, 727 (2023).
- [4] M. Fujita *et al.*, J. Phys. Soc. Jpn. **65**, 1920 (1996).
- [5] T. Matsui *et al.*, in preparation.
- [6] MH. Bae *et al.*, Nat. Commun. **4**, 1734 (2013).
- [7] Y. Hu *et al.*, Appl. Phys. Lett. **95**, 233116 (2009).
- [8] ZW. Tan *et al.*, Nano Lett. **11**, 214 (2011).
- [9] T. Yokosawa *et al.*, e-J. Surf. Sci. Nanotechnol. **20**, 139 (2022).
- [10] I. Calizo *et al.*, Nano Lett. **7**, 2645 (2007).
- [11] J. Judek *et al.*, Sci. Rep. **5**, 12422 (2015).
- [12] J. H. Seol *et al.*, Science **328**, 213 (2010).