EE412 Black Magic (BM) Pro 4” Graphene Development and Optimization

6-3-2015

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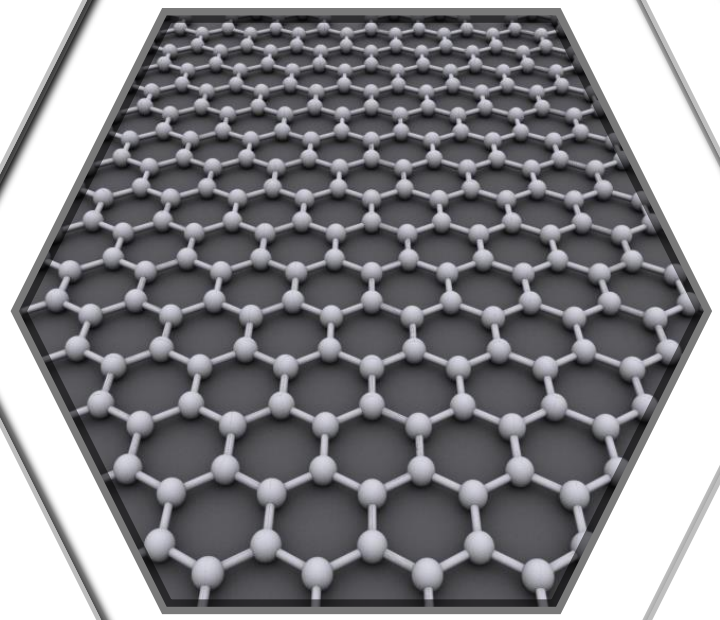
Staff Advisor: Dr. Yong Cheol Shin

SNF Staff Advisors: Michelle Rincon, Ted Berg, Robert Chen

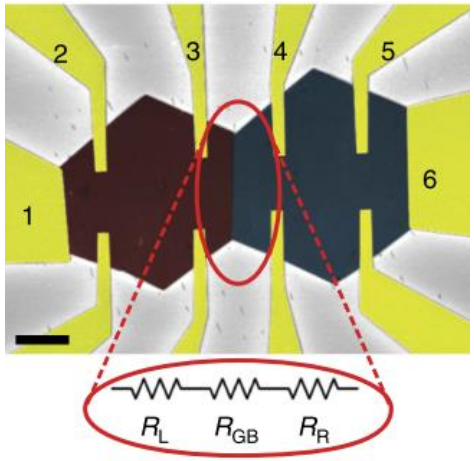
“Beyond Moore” Electronics



w/ Graphene

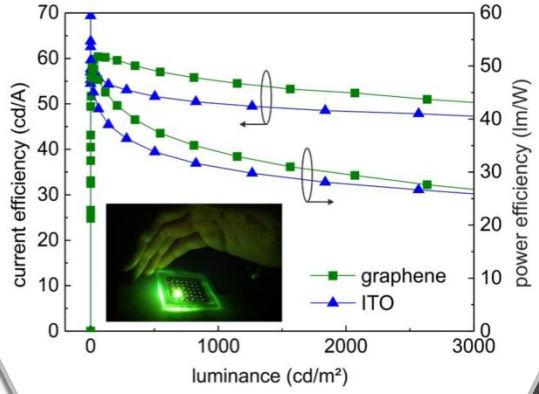
High electrical mobility
Thin & Flexible

Next-Gen Sensors



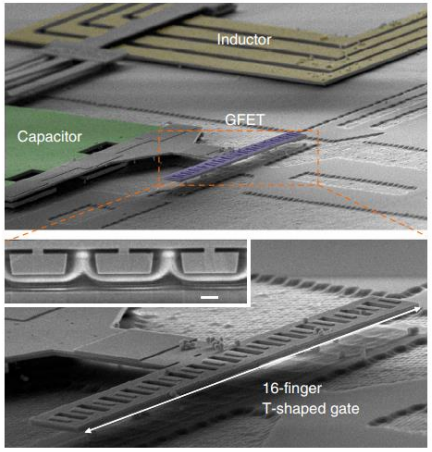
P. Yasaei, *et al.*, *Nat. Comm.*, (2014)

Transparent Electronics



J. Meyer, et al., *Sci. Rep.*, **4**, 5380 (2014)

Analog Electronics

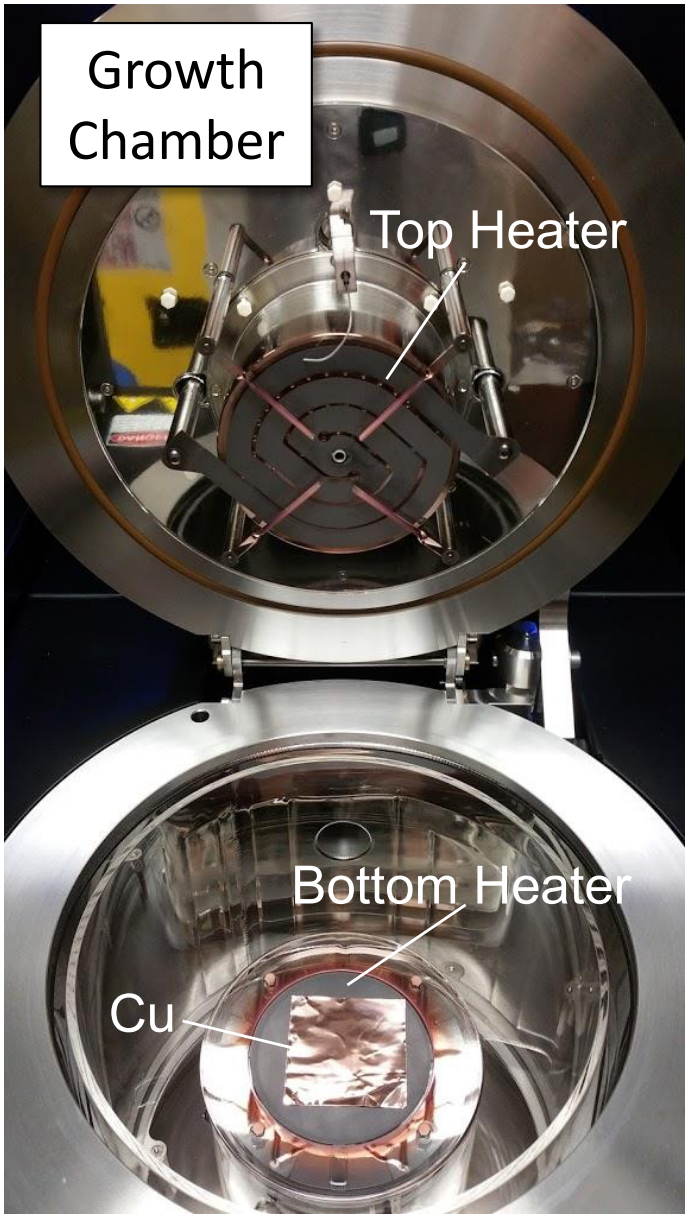


S.-J. Han, et al., *Nat. Comm.*, **5**, 3086 (2014)

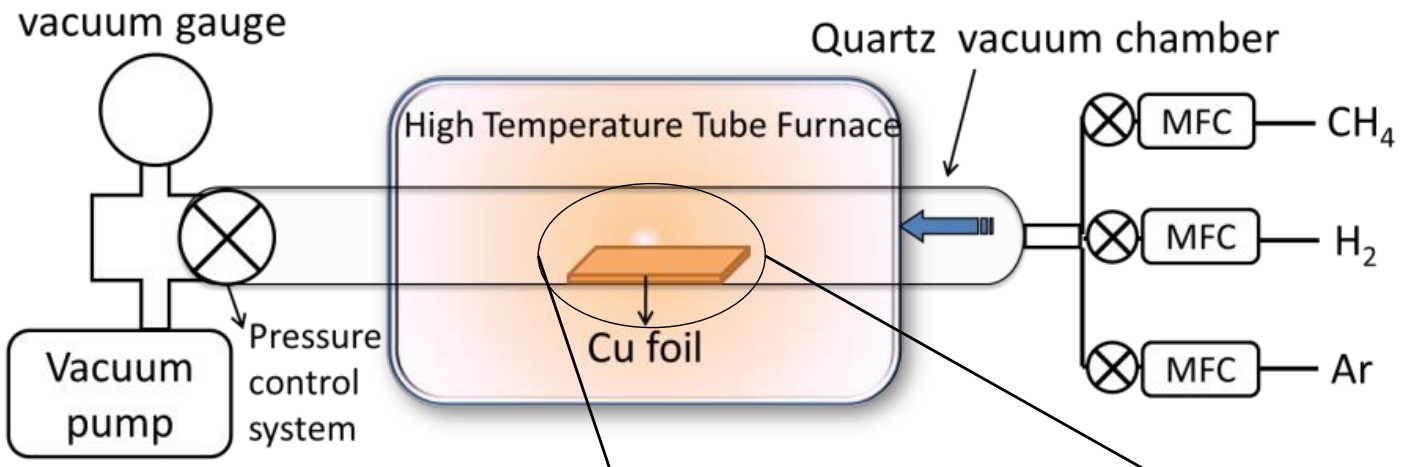
Flexible Electronics

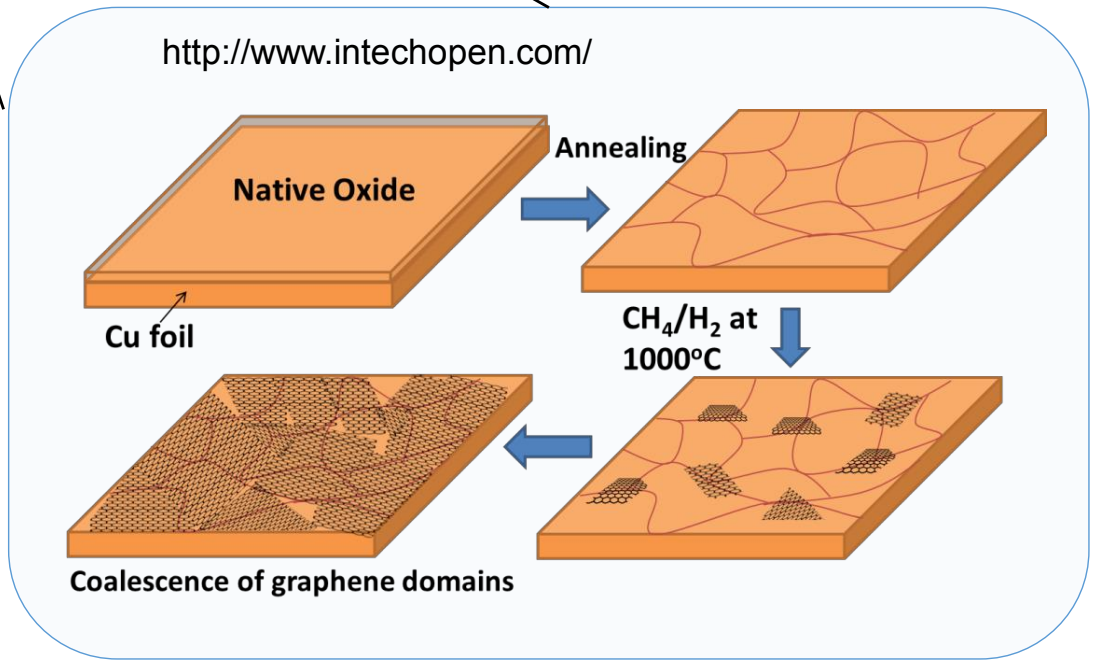
Plastic Logic

Graphene @ SNF



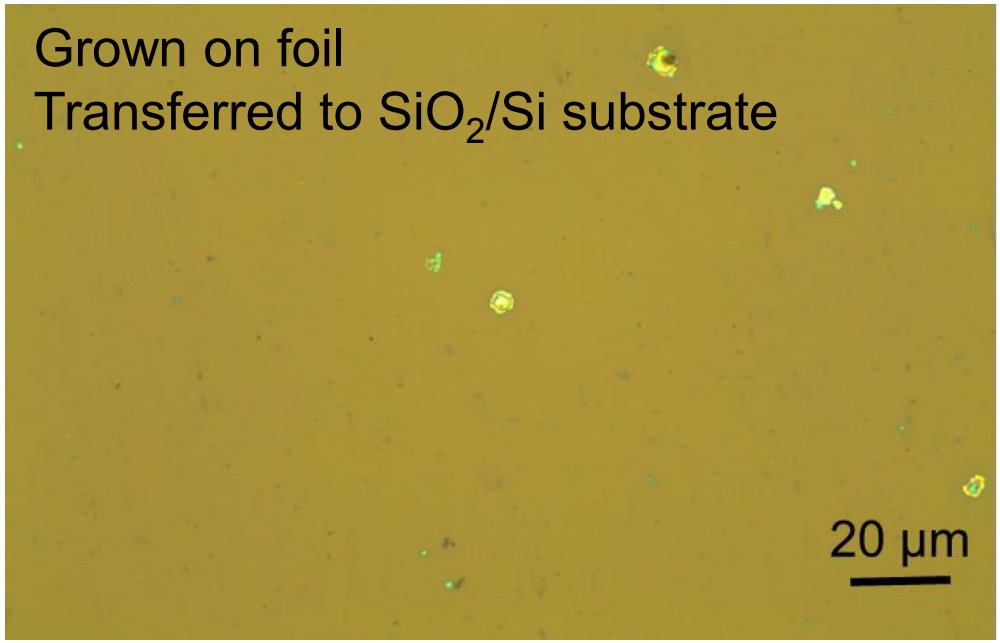
Chemical Vapor Deposition of Graphene

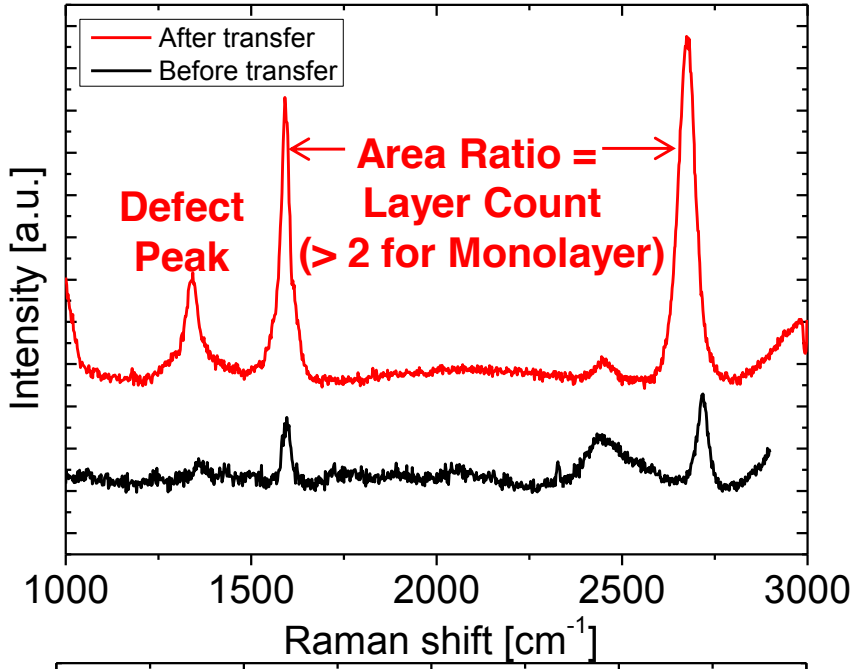


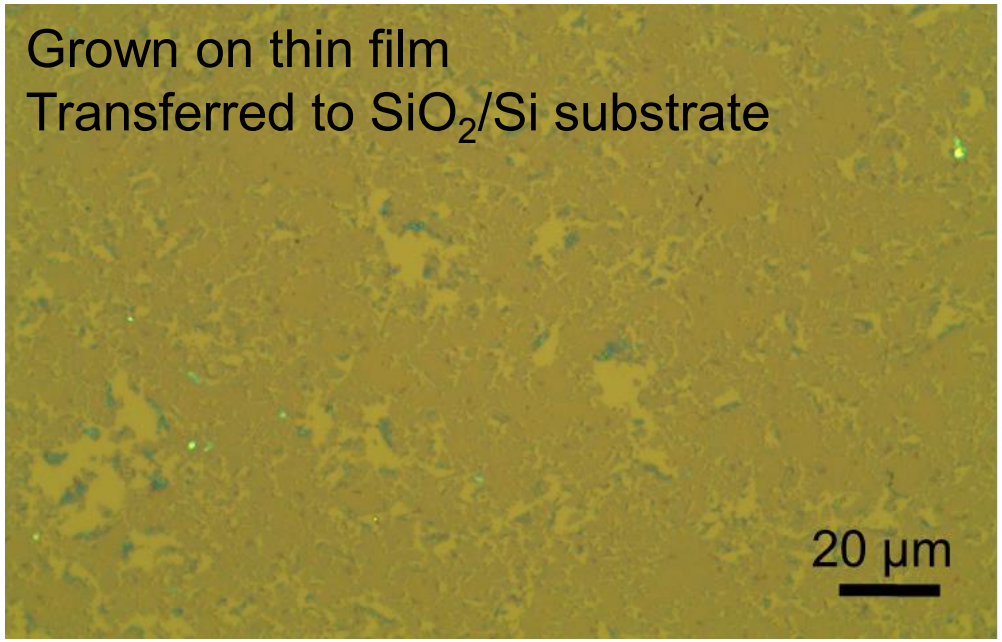


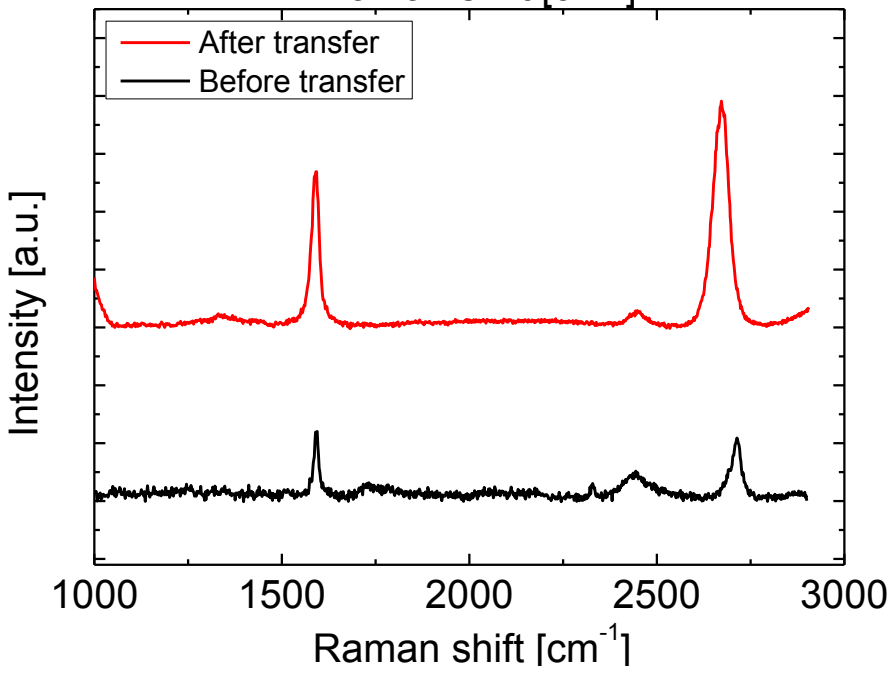
Growth Development

Raman Results - Aixtron Base Recipes

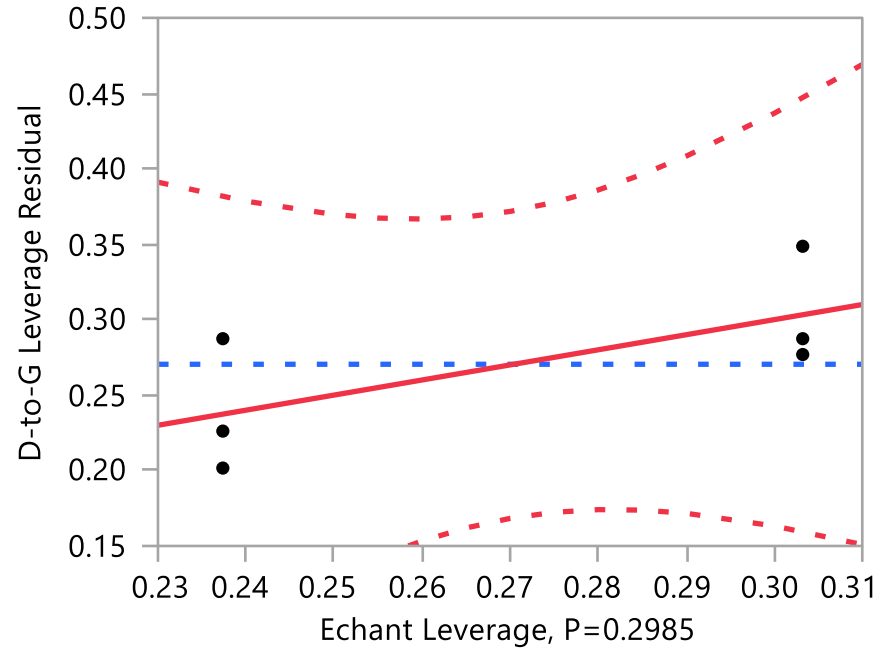




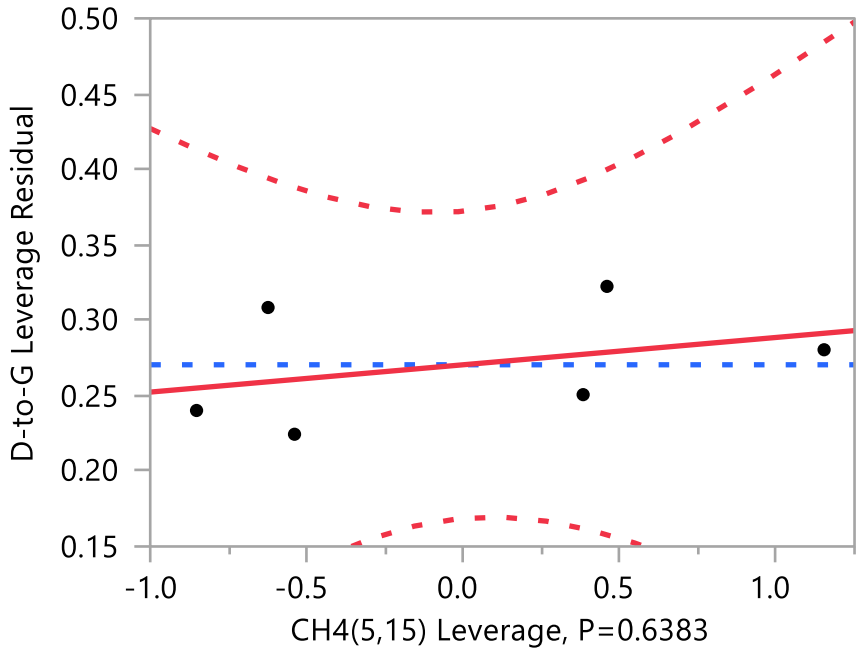


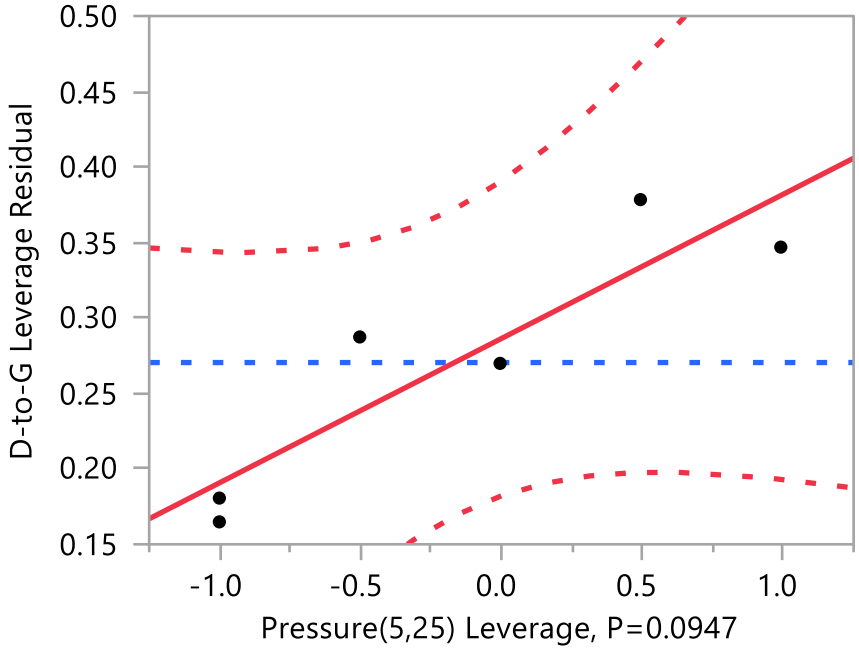


Foil Growth

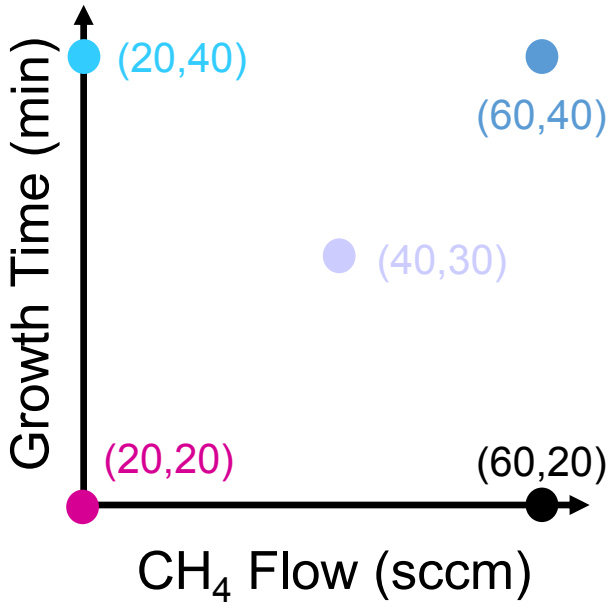


Parameters			Results	
Etch	CH_4 (sccm)	Pres (mb)	D/G	2D/G
Ni	10	5	0.19	3.5
Ni	15	25	0.48	2.64
Ni	5	10	0.24	2.51
HCl	5	5	0.18	3.01
HCl	10	25	0.48	2.64
HCl	15	10	0.21	3.32



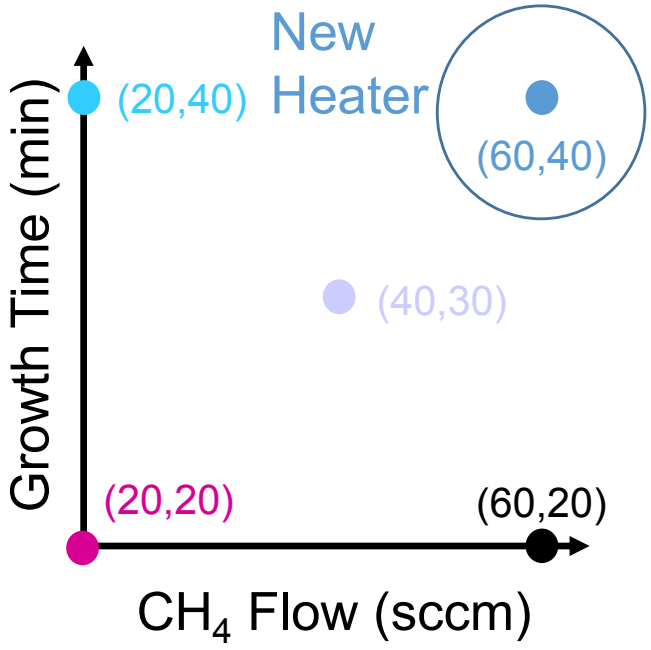


Thin Film Growths



Run	Center D/G	Center 2D/G	Edge D/G	Edge 2D/G
(20,20)				
(60,20)				
(20,40)				
(40,30)				
(60,40)				

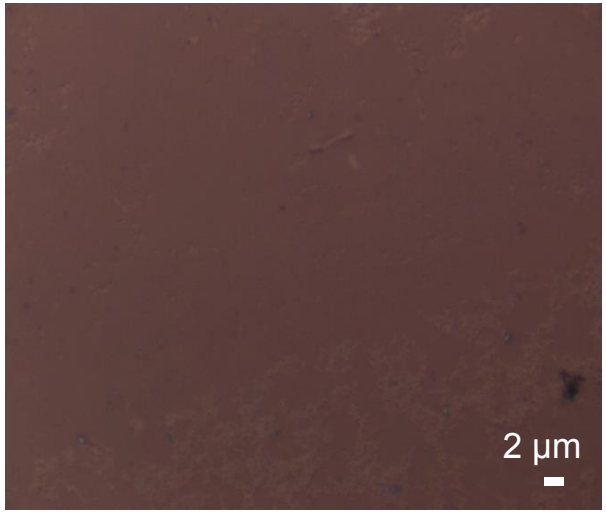
Thin Film Growths

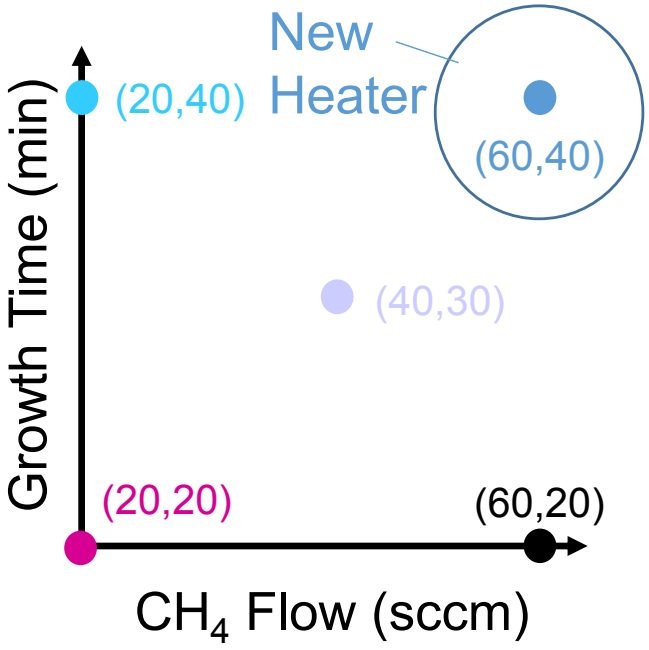


Run	Center D/G	Center 2D/G	Edge D/G	Edge 2D/G
(20,20)	0.16	3.71	0.30	2.54
(60,20)	0.09	4.39	0.39	3.81
(20,40)	0.11	2.57	0.09	4.39
(40,30)	1.46	1.37	1.63	3.81
(60,40)				

Thin Film Growths

Run 37 (60,40), 50X





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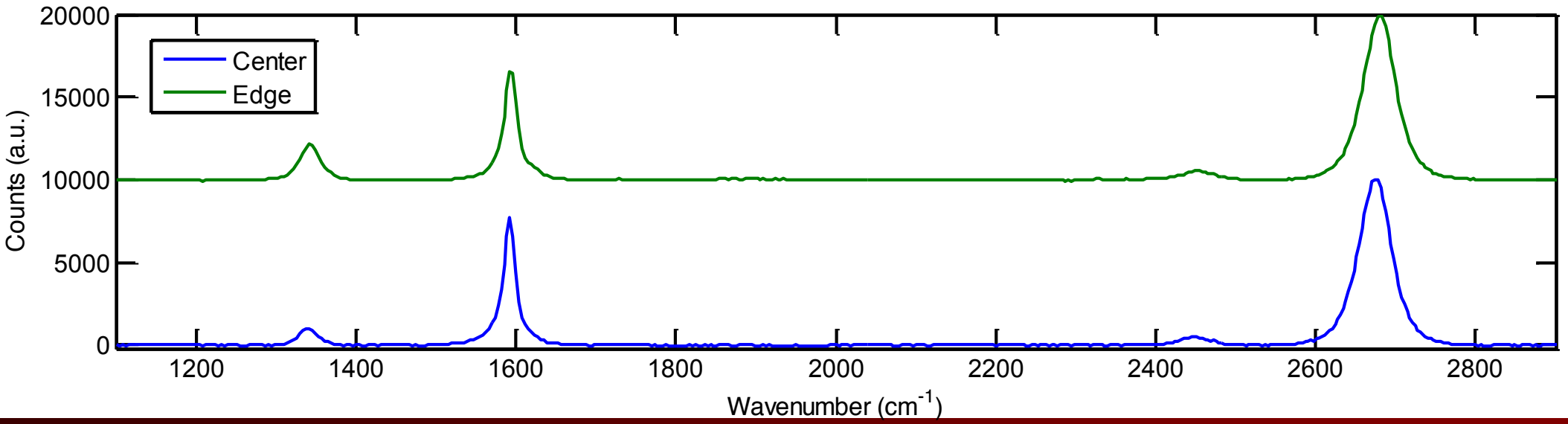
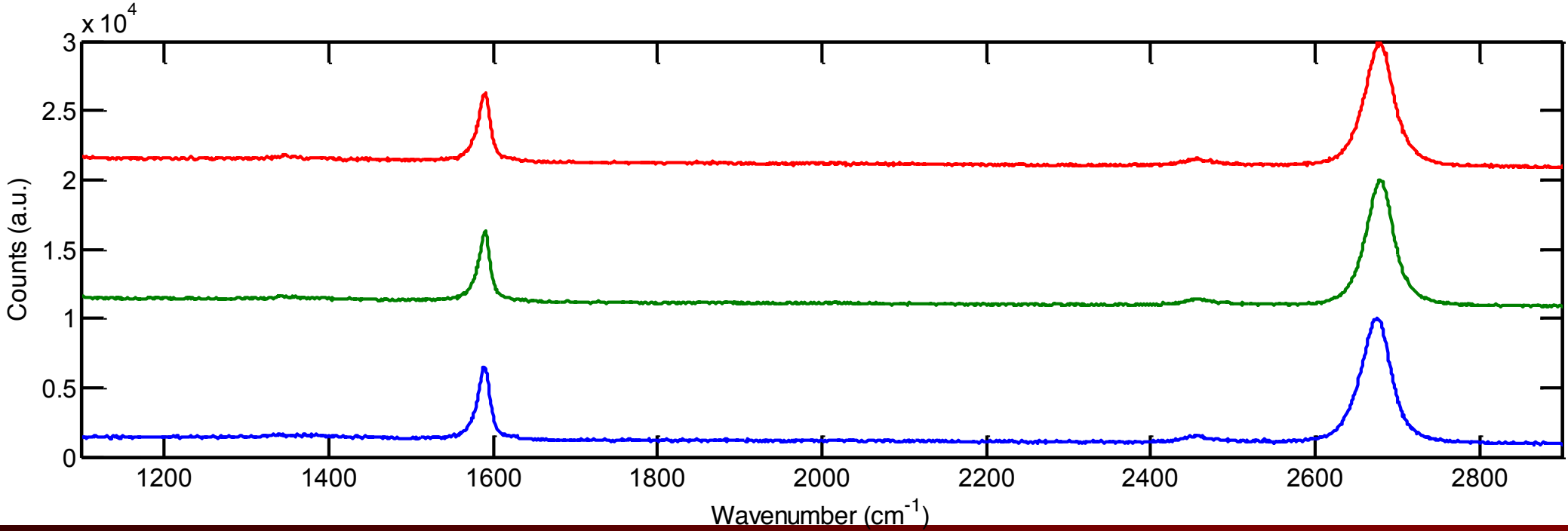
(40,30)	1.46	1.37	1.63	3.81
(60,40)	**0.19**	**3.22**	**0.46**	**3.32**

Run 37 (60,40)



High Quality Treatment/Foils

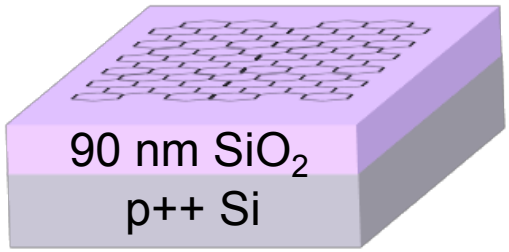
- Experimental growths run by Dr. Yong Cheol
- Substrate – High Purity Cu from JX
- Surface treatment w/ acetic acid
- Reduced Ar flow
- Low pressure



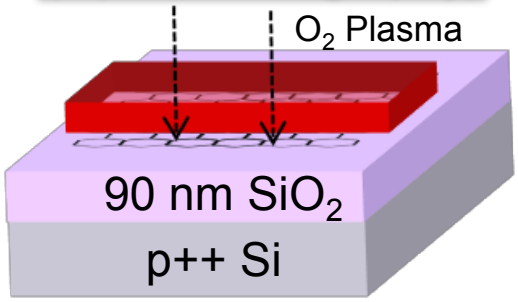
Electrical Characterization

TLM Structures: Fabrication Details

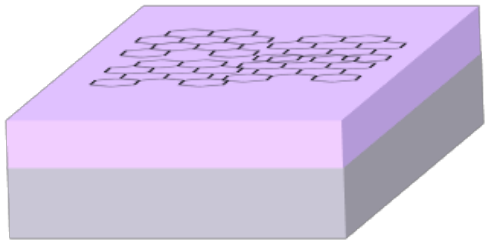
1. Transfer Graphene



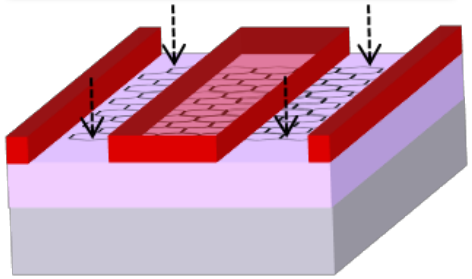
2. Define Channel (Optical Lithography)



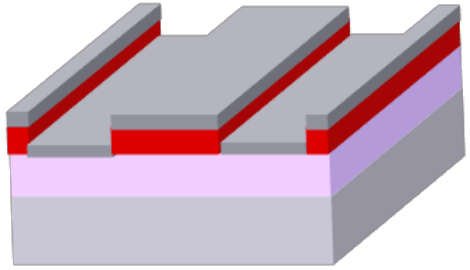
3. Remove PR



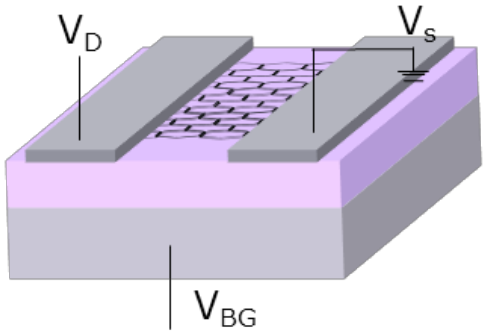
4. Define Contacts (Optical Lithography)



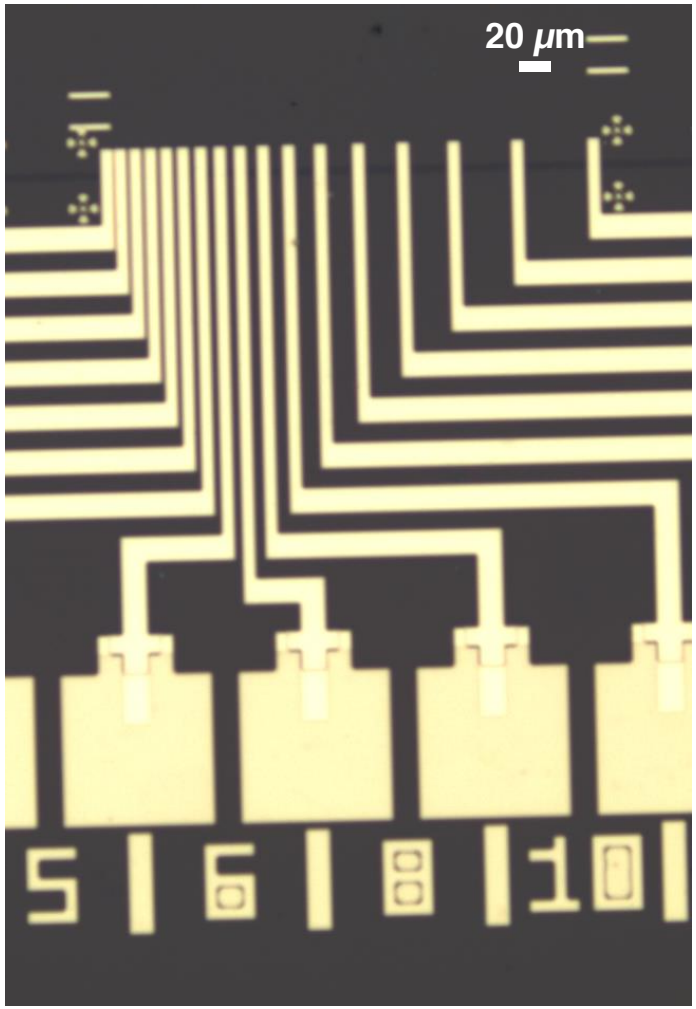
5. Metal Deposition (40 nm Pd, e-beam)



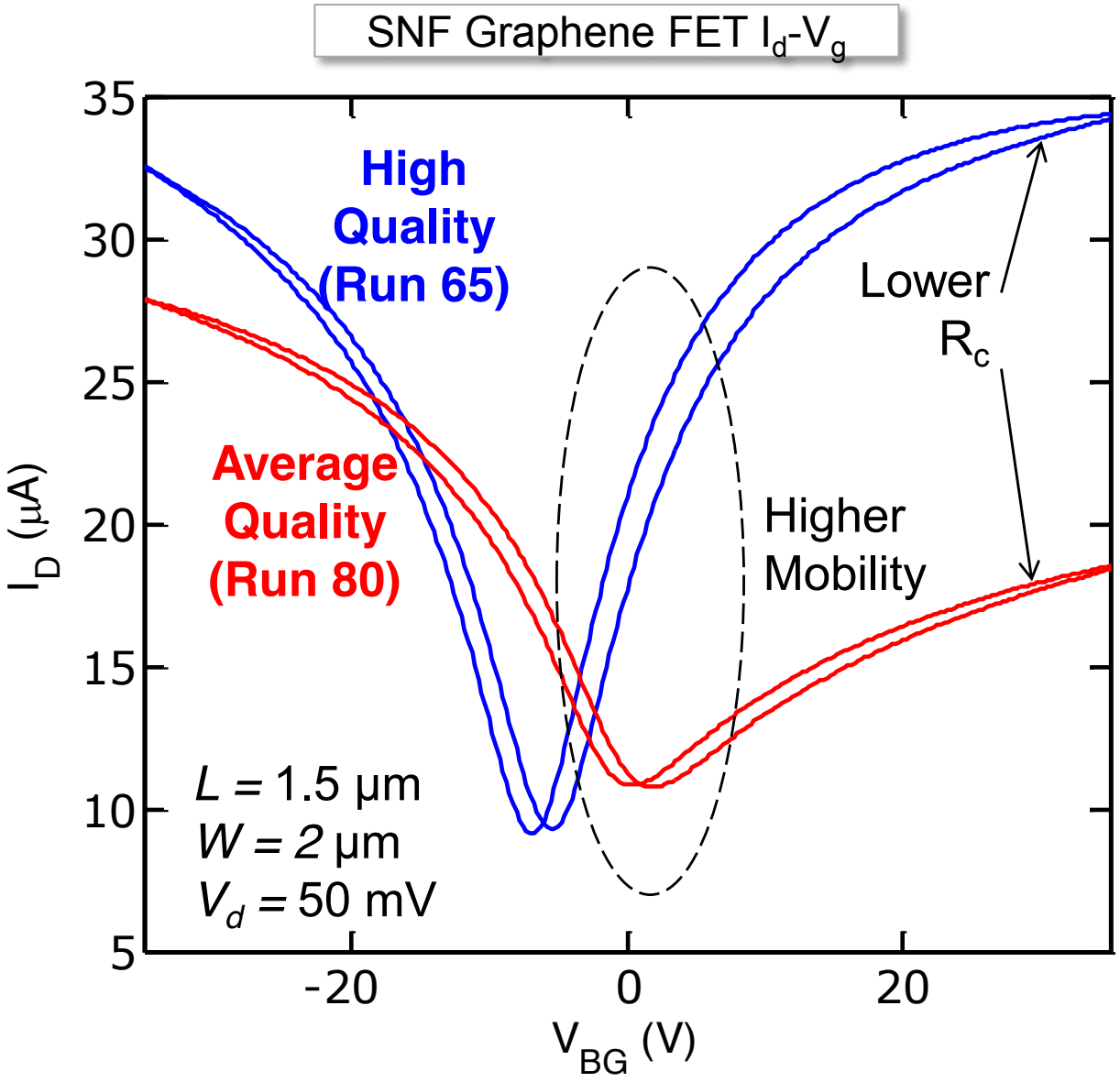
6. Liftoff



TLM Structure
10x Optical Image



Electrical Results – Qualitative Comparison



Fit Model

$$R_{d,fit} = \frac{L}{W} R_s + 2R_C + R_{series}$$

Sheet Resistance

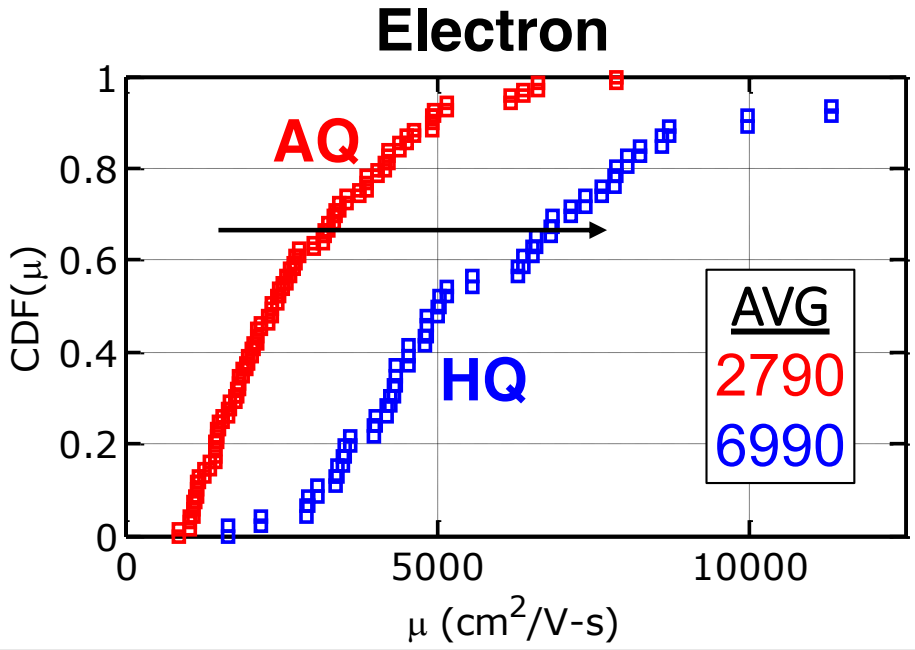
$$R_s = \frac{1}{q\mu_0(n+p)}$$

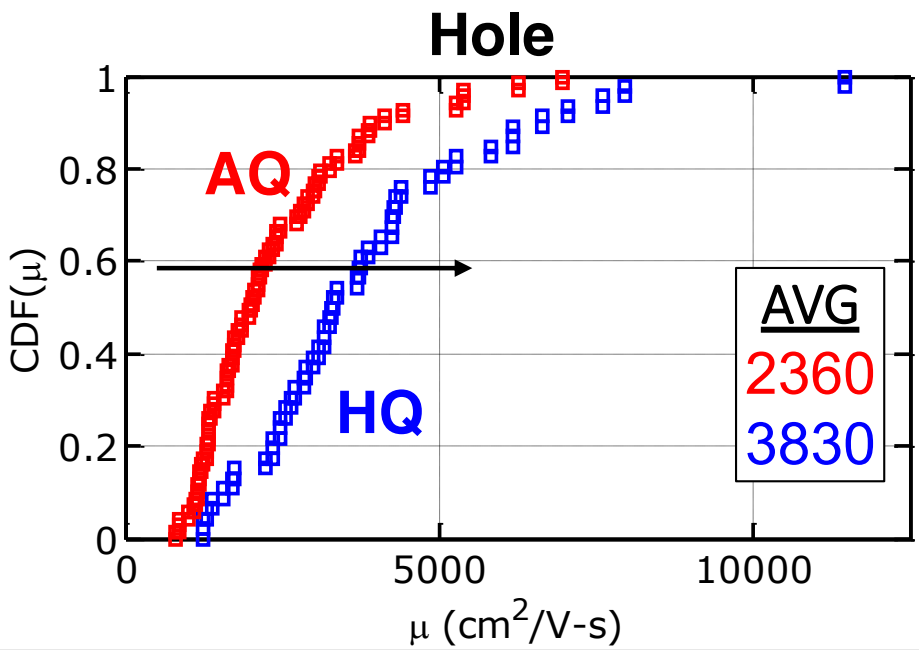
Contact Resistance

$$R_c = \frac{1}{W}\frac{\rho_C}{L_T}\coth\left(\frac{L_C}{L_T}\right), L_T = \sqrt{\frac{\rho_C}{R_S}}$$

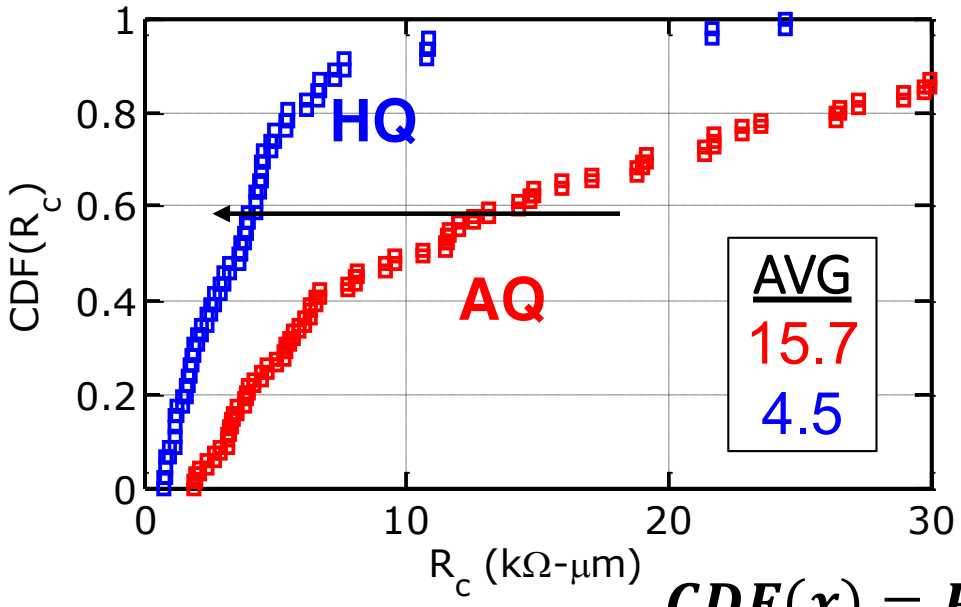
Electrical Results – Statistical Comparison

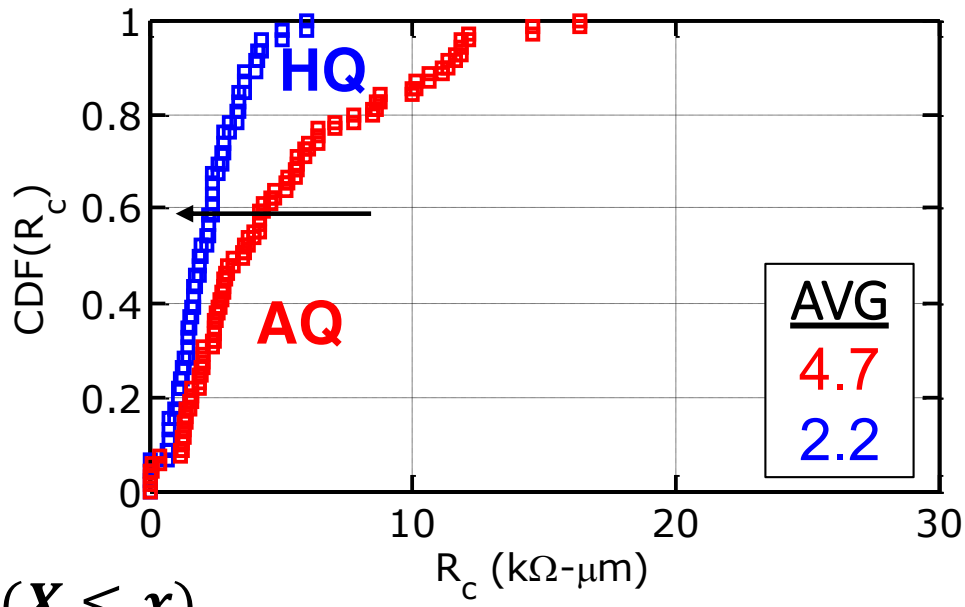
Intrinsic Mobility





Contact Resistance





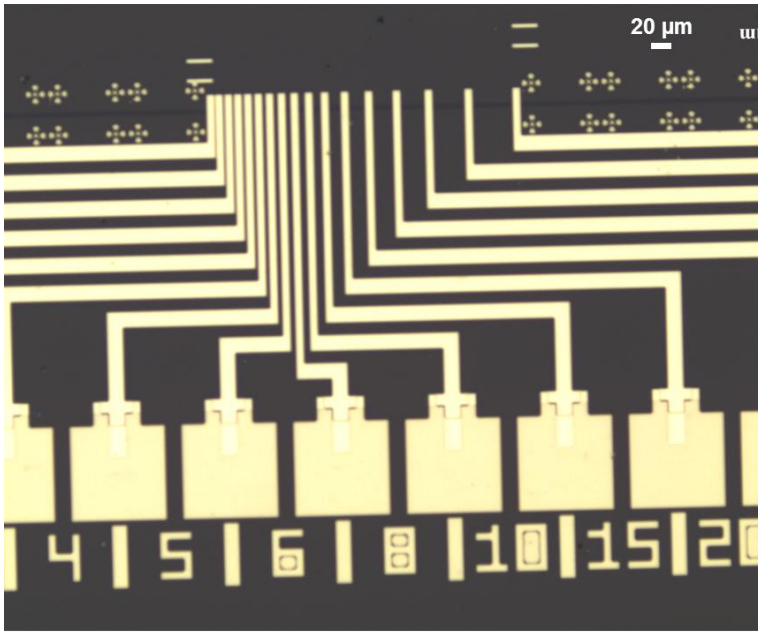
$$CDF(x) = P(X \leq x)$$

Conclusion

- SNF BM Pro 4” Furnace Development:
  →Recipes refined w/DOE
  →>100 successful growths!
- Mass elec. characterization confirms high graphene quality
- Quality dependent on substrate type, prep:

Type	Cu Purity	Grain Size (μm)	μ_e (cm^2/V-s)	μ_h (cm^2/V-s)
AQ	99.8%	0.5-1	~2800	~2300
HQ	99.9%	>10	~6900	~3800

SNF now ready for graphene!



Thanks to:

Yong Cheol Shin

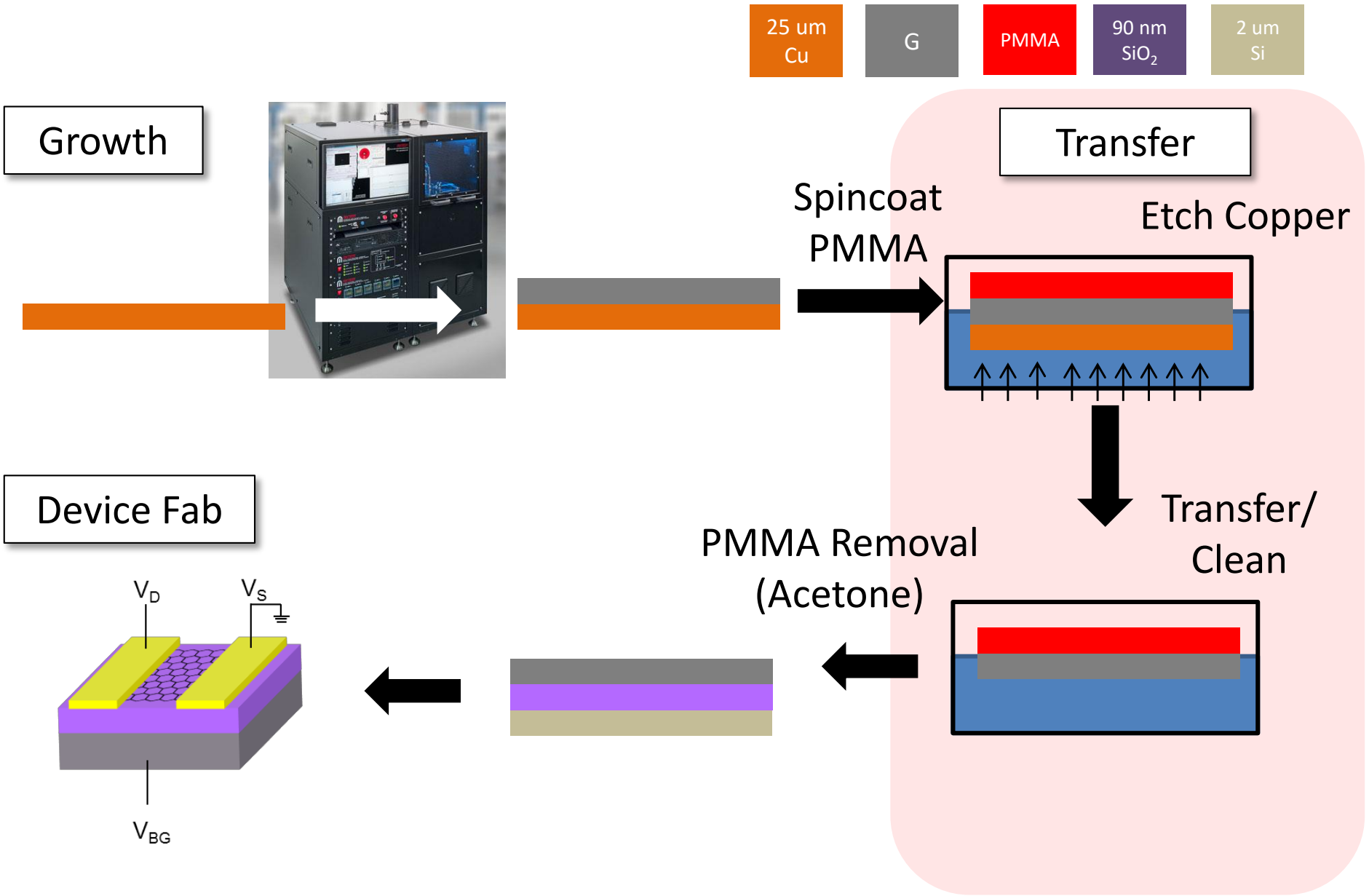
Michelle Rincon

Robert Chen

Ted Berg

Aixtron Technical Support: Nigel Bradley, Ken Teo

GFET Fabrication



Pop Lab Graphene Model

Total Device Resistance

$$R_{d,fit} = \frac{L}{W} R_s + 2R_C + R_{series}$$

Contact Resistance

$$R_c = \frac{1}{W}\frac{\rho_C}{L_T}\coth\left(\frac{L_C}{L_T}\right) \approx \sqrt{\rho_c R_S} \text{ for } L_C >> L_T = \sqrt{\frac{\rho_C}{R_S}}$$

Sheet Resistance

$$R_s = \frac{1}{q\mu_0(n+p)}$$

Carrier Con.

$$n = \frac{1}{2}\left[n_{cv} + \sqrt{n_{cv}^2 + 4n_{ip}^2}\right]$$

Impurity Conc.

$$n_{ip} = \sqrt{\left(\frac{n_0}{2}\right)^2 + n_i^2}$$

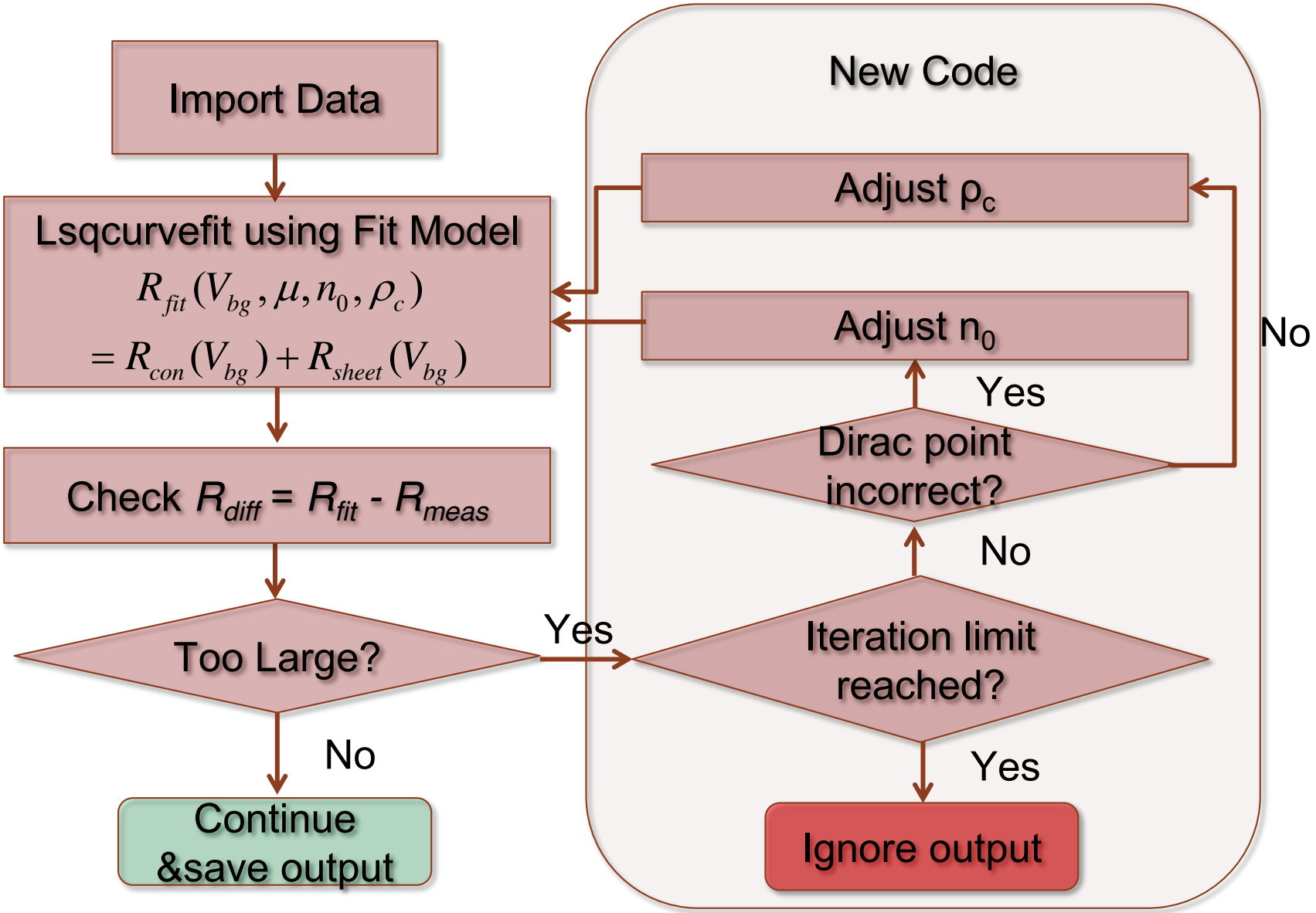
Thermal Carriers

$$n_i = \frac{\pi}{6}\frac{k_b T}{\hbar v_F}^2$$

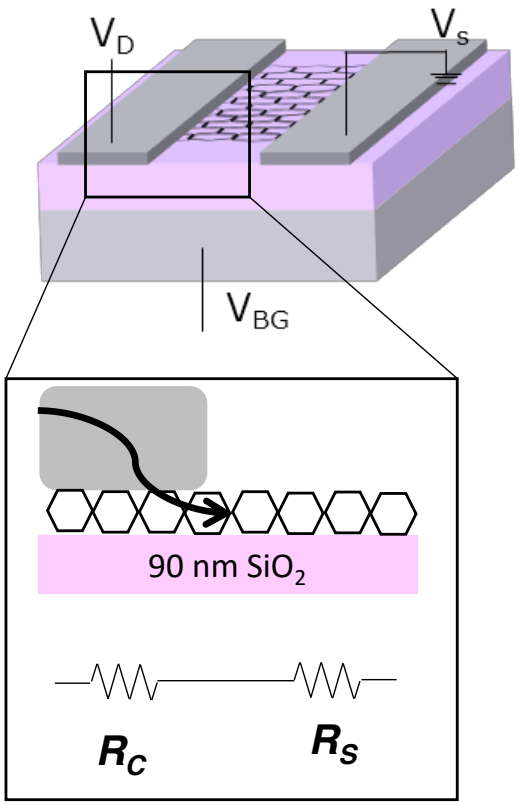
Electrostatic Doping

$$n_{cv} = C_{ox}(V_0 - V_{bg})/q$$

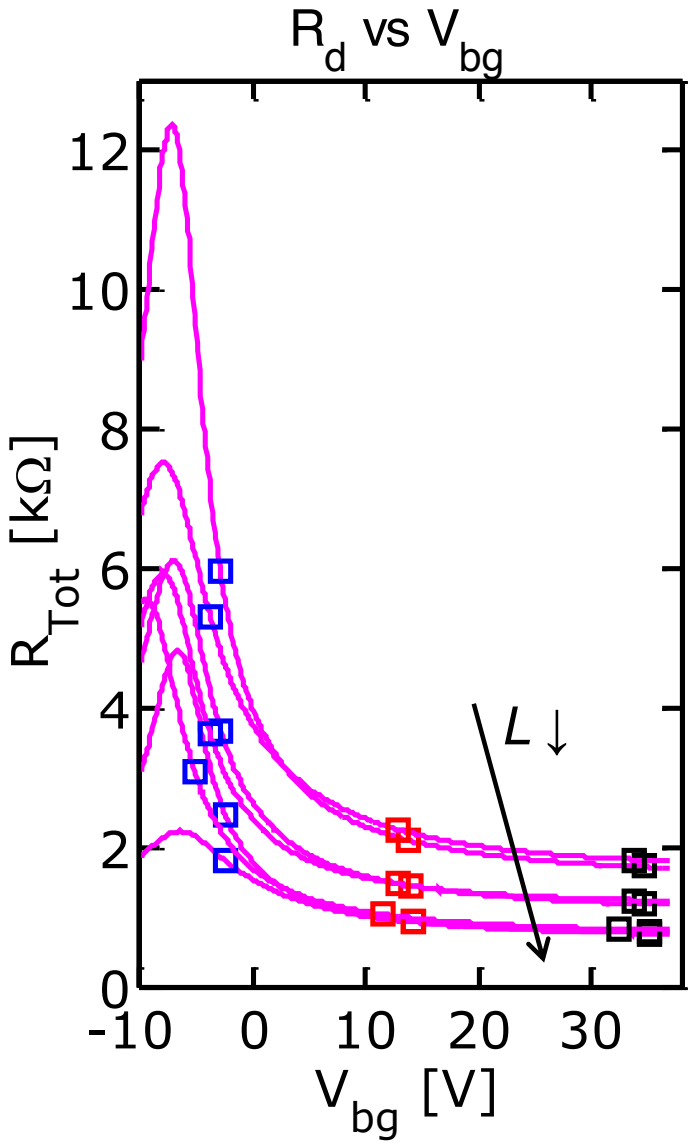
Pop Lab Graphene Model

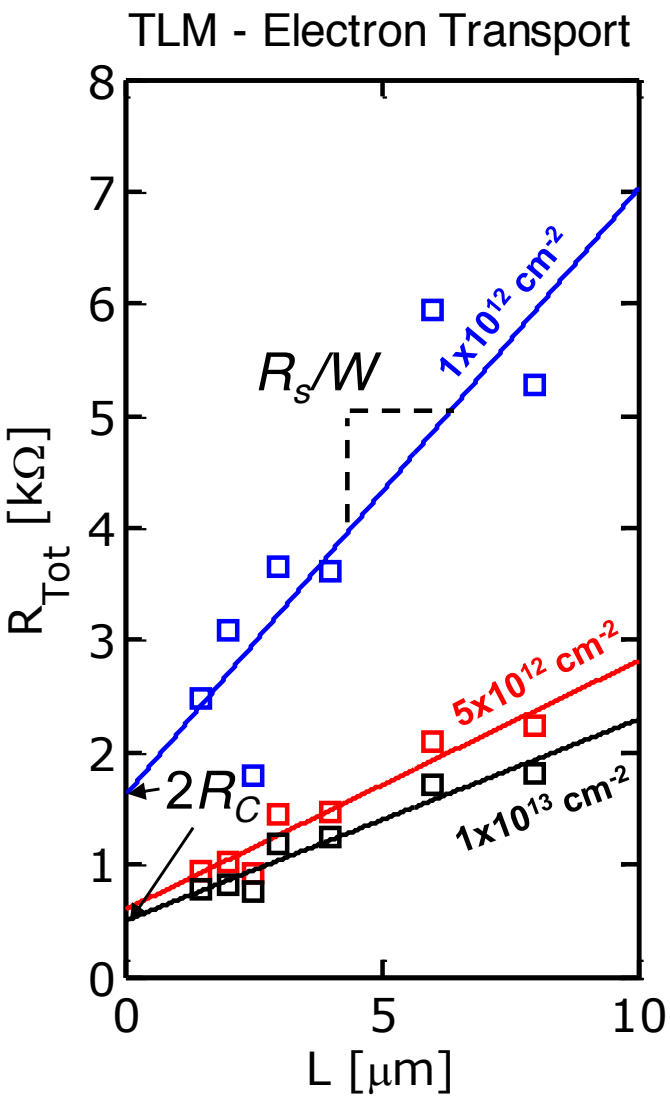


TLM Structures: Extracting R_C

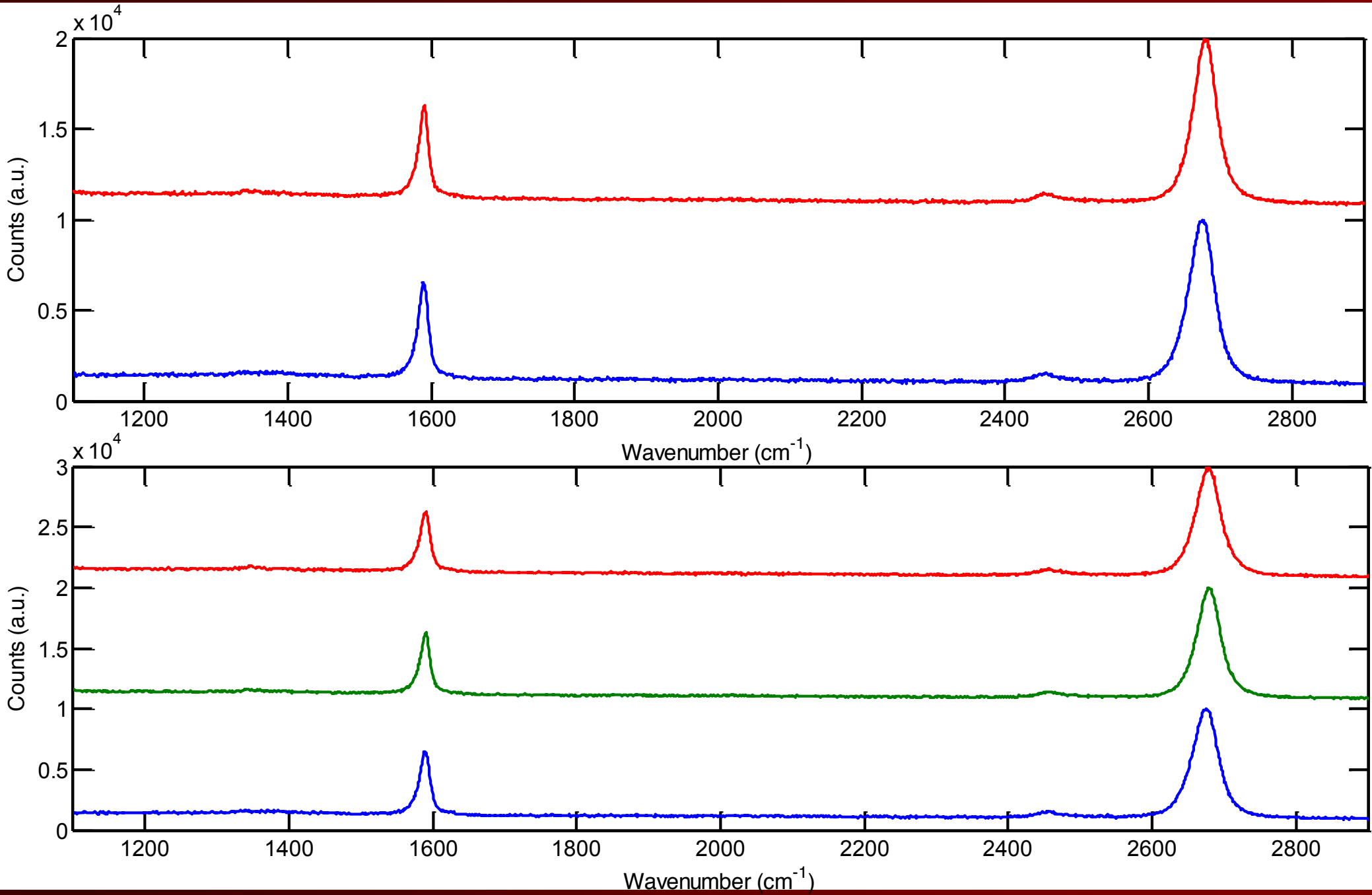


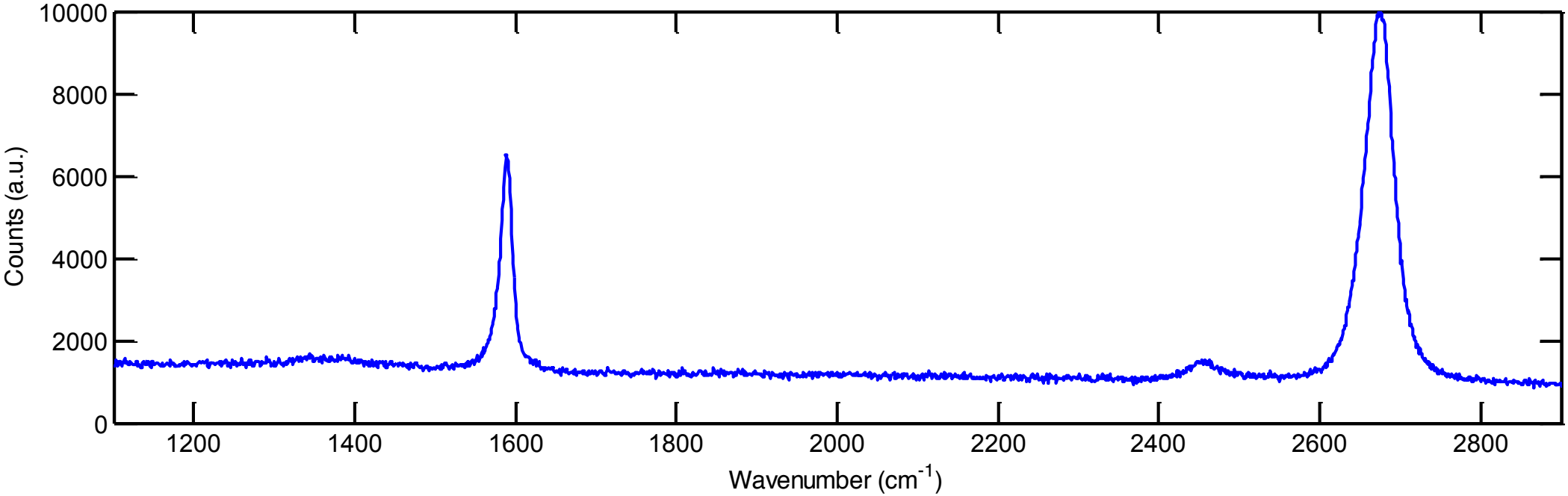
$$R_{TOT} = \frac{R_s}{W} L + 2R_C$$



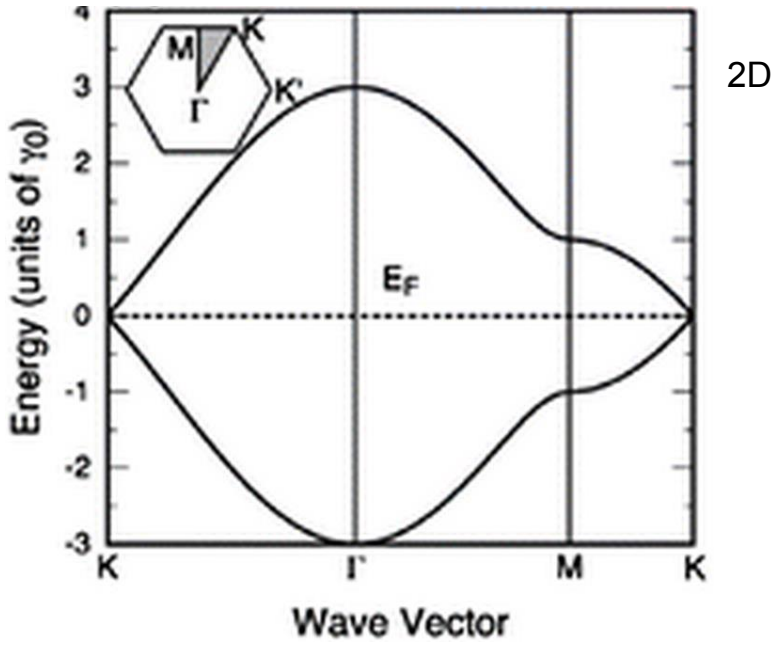


Run 65

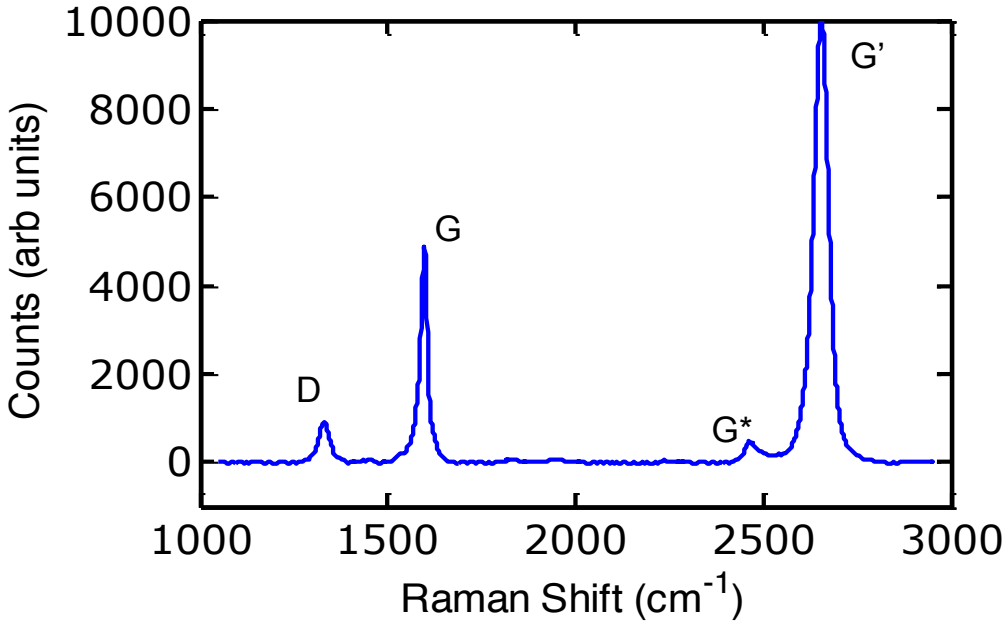

x 10^4
2
1.5
1
0.5
0
Counts (a.u.)
1200
1400
1600
1800
2000
2200
2400
2600
2800
Wavenumber (cm^-1)
x 10^4
3
2.5
2
1.5
1
0.5
0
Counts (a.u.)
1200
1400
1600
1800
2000
2200
2400
2600
2800
Wavenumber (cm^-1)

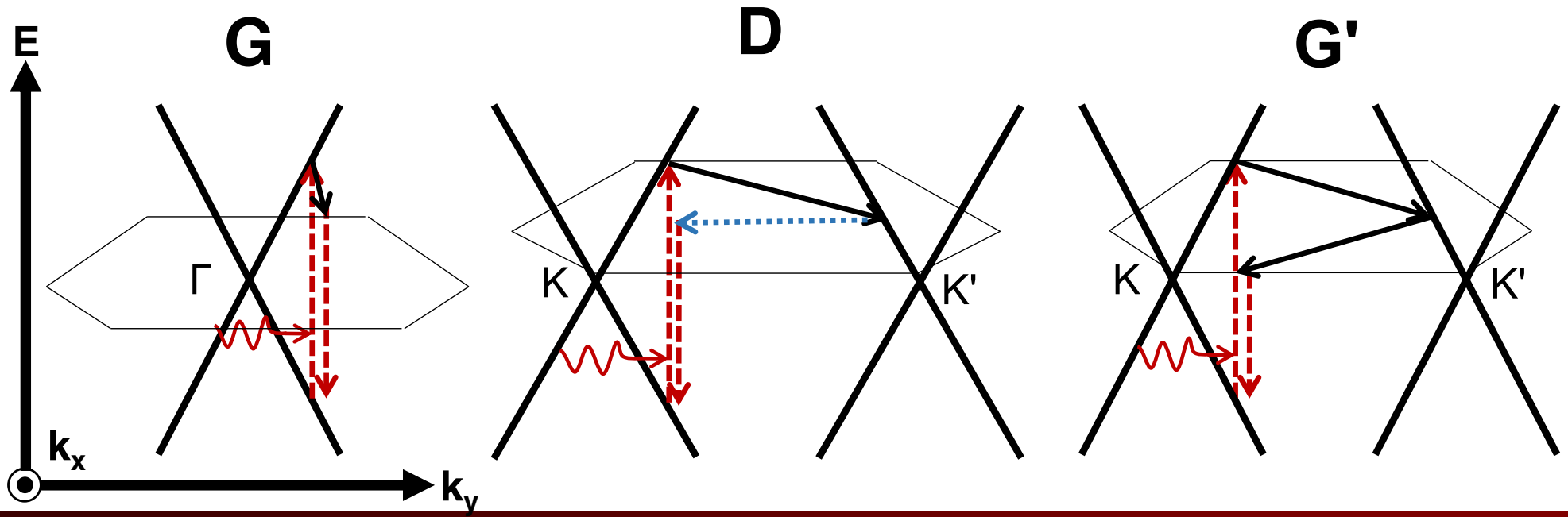

10000
8000
6000
4000
2000
0
Counts (a.u.)
1200
1400
1600
1800
2000
2200
2400
2600
2800
Wavenumber (cm-1)

Raman – Qualification Method

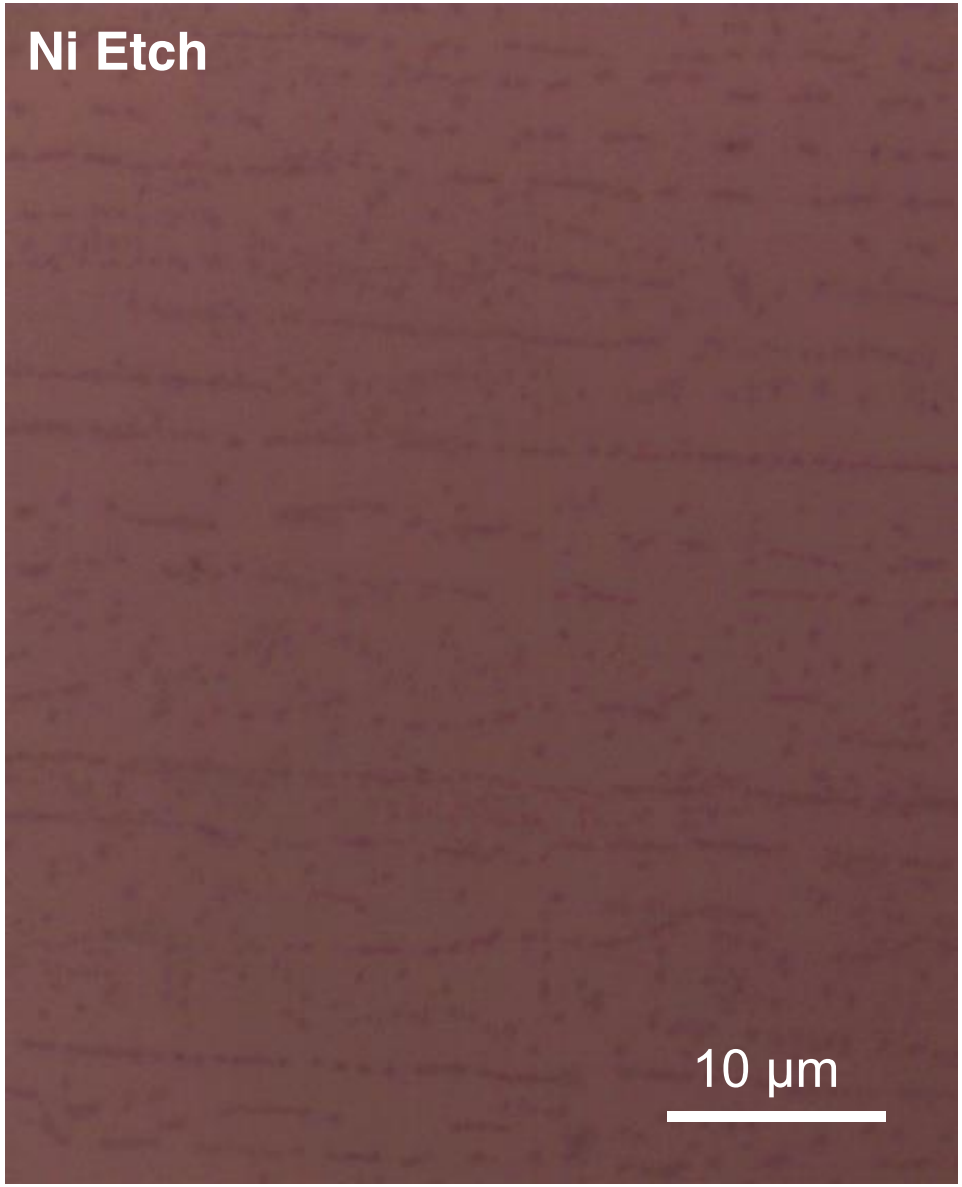


2D

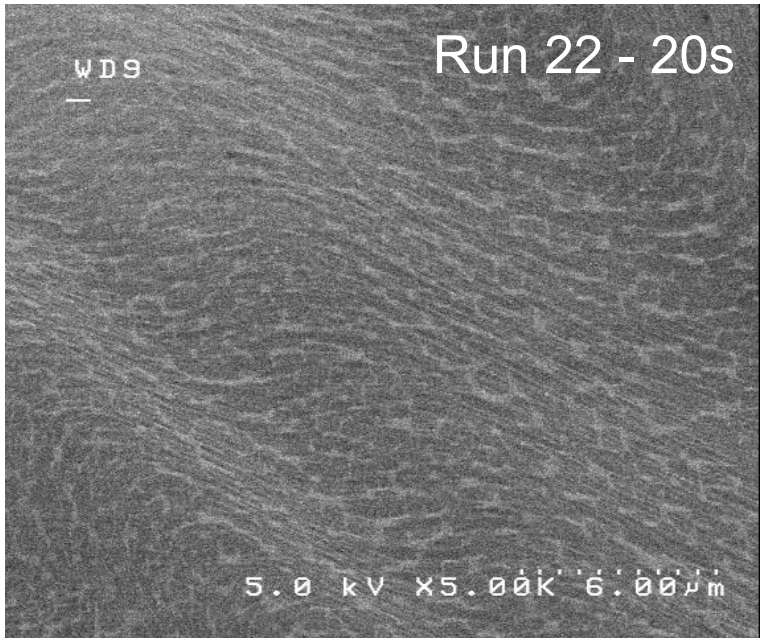


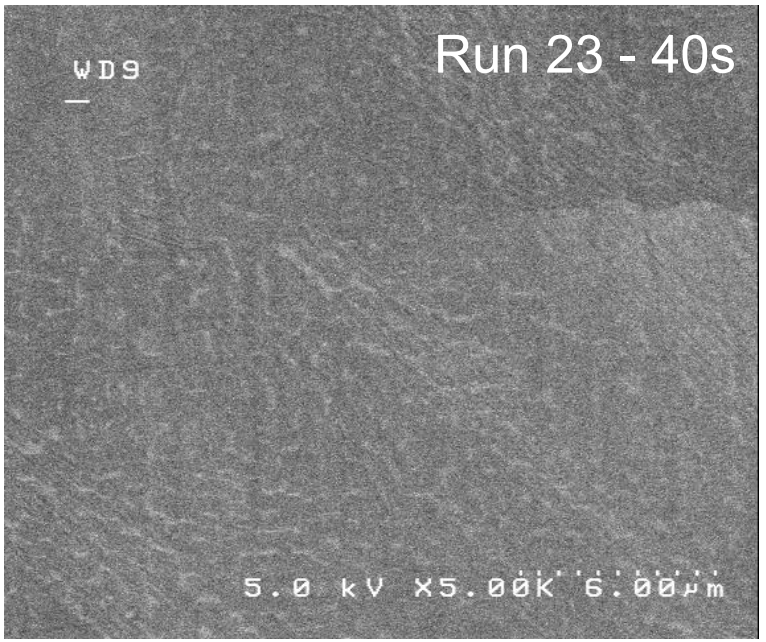


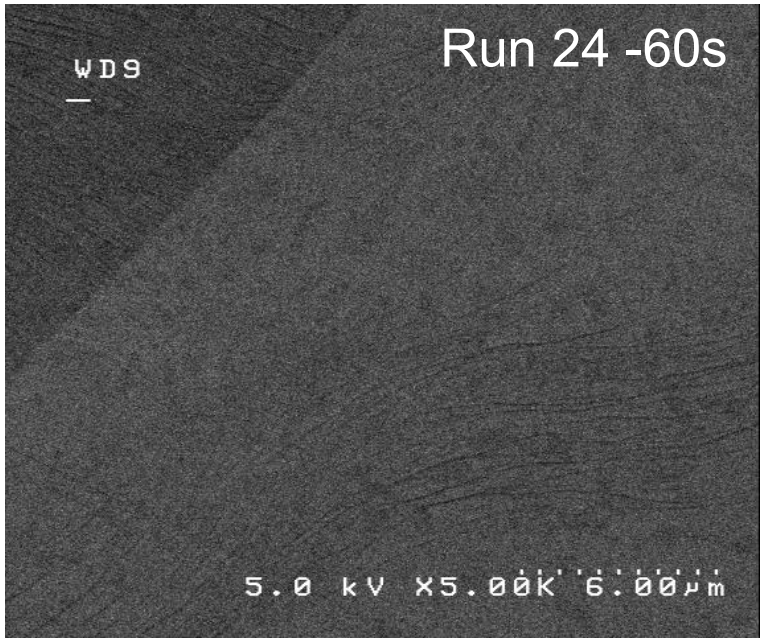

HCl


Ni Etch
10 µm

Current Growth Progress – Copper Foil Grain Size







- High growth rate
- Small grain size: ~ 1 µm
- Local bilayer

→ H_2/Ar/CH_4 flow rate ratio control