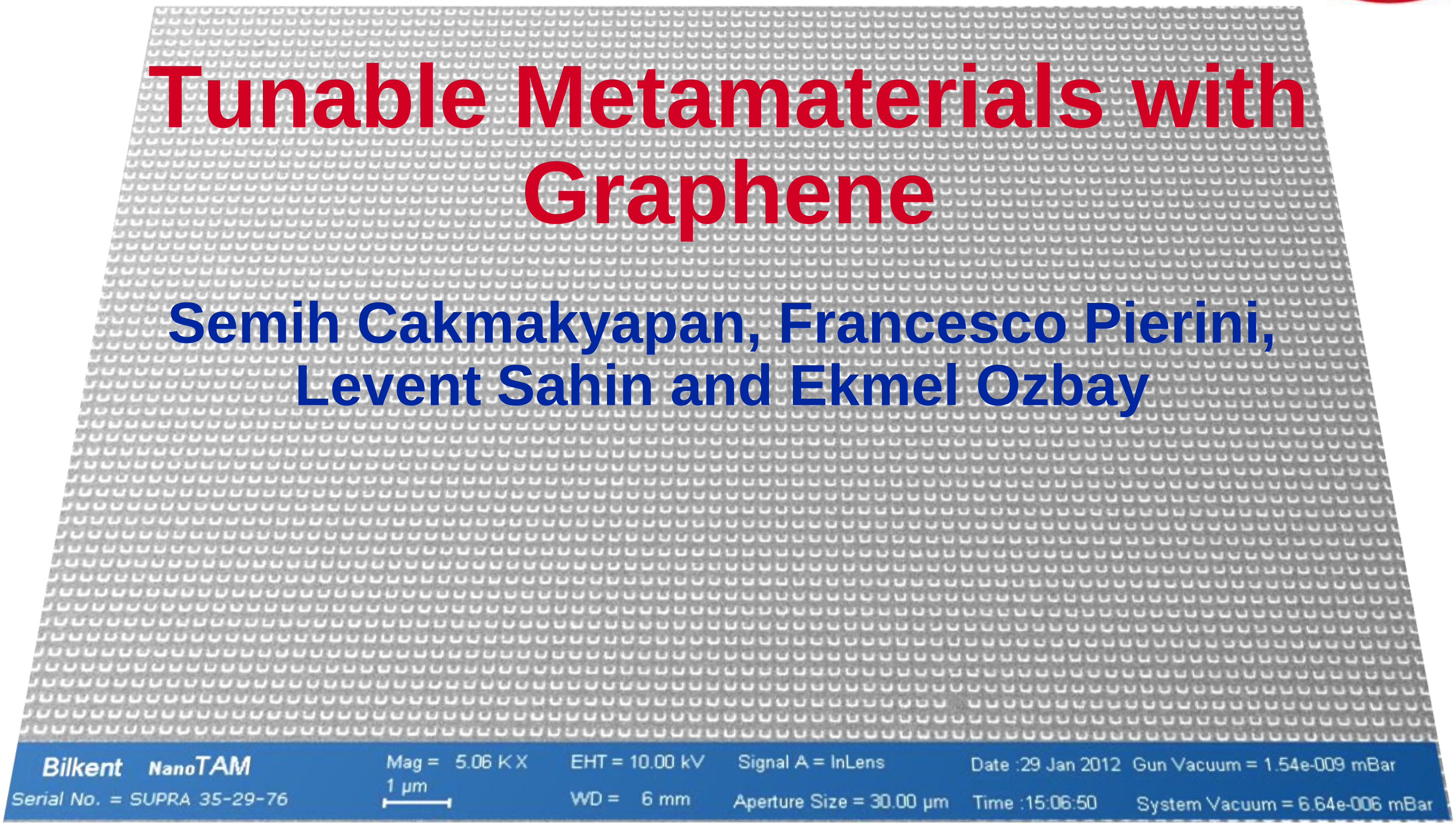
Tunable Metamaterials with Graphene

Semih Cakmakyapan, Francesco Pierini, Levent Sahin and Ekmel Ozbay



Outline

- Properties of our graphene samples
- Overview of the past graphene studies
- Graphene plasmonics
- Fabrication details
- Experimental and Simulation Results
- Conclusion

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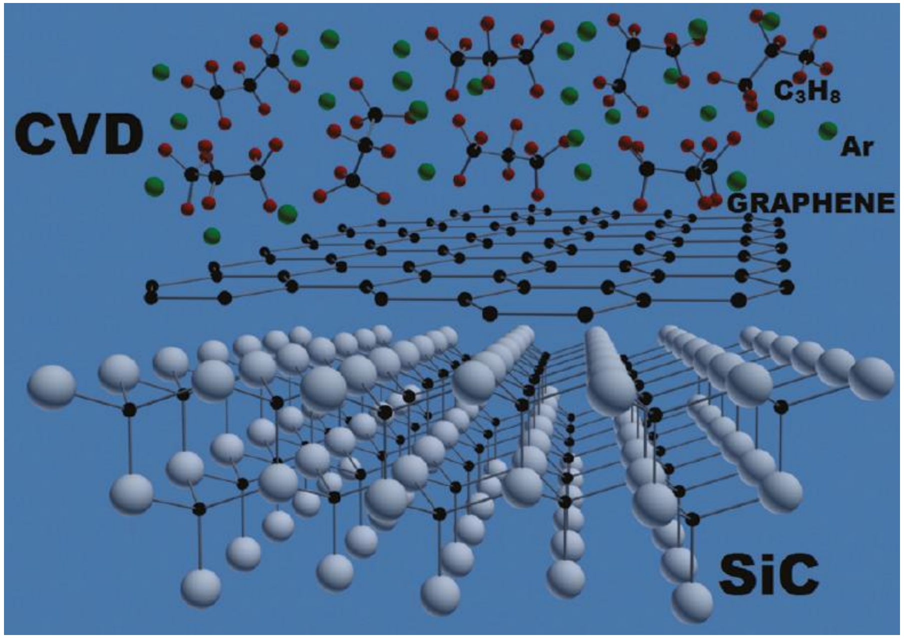
ITME

LINKÖPINGS UNIVERSITET

İhsan Doğramacı Bilkent University

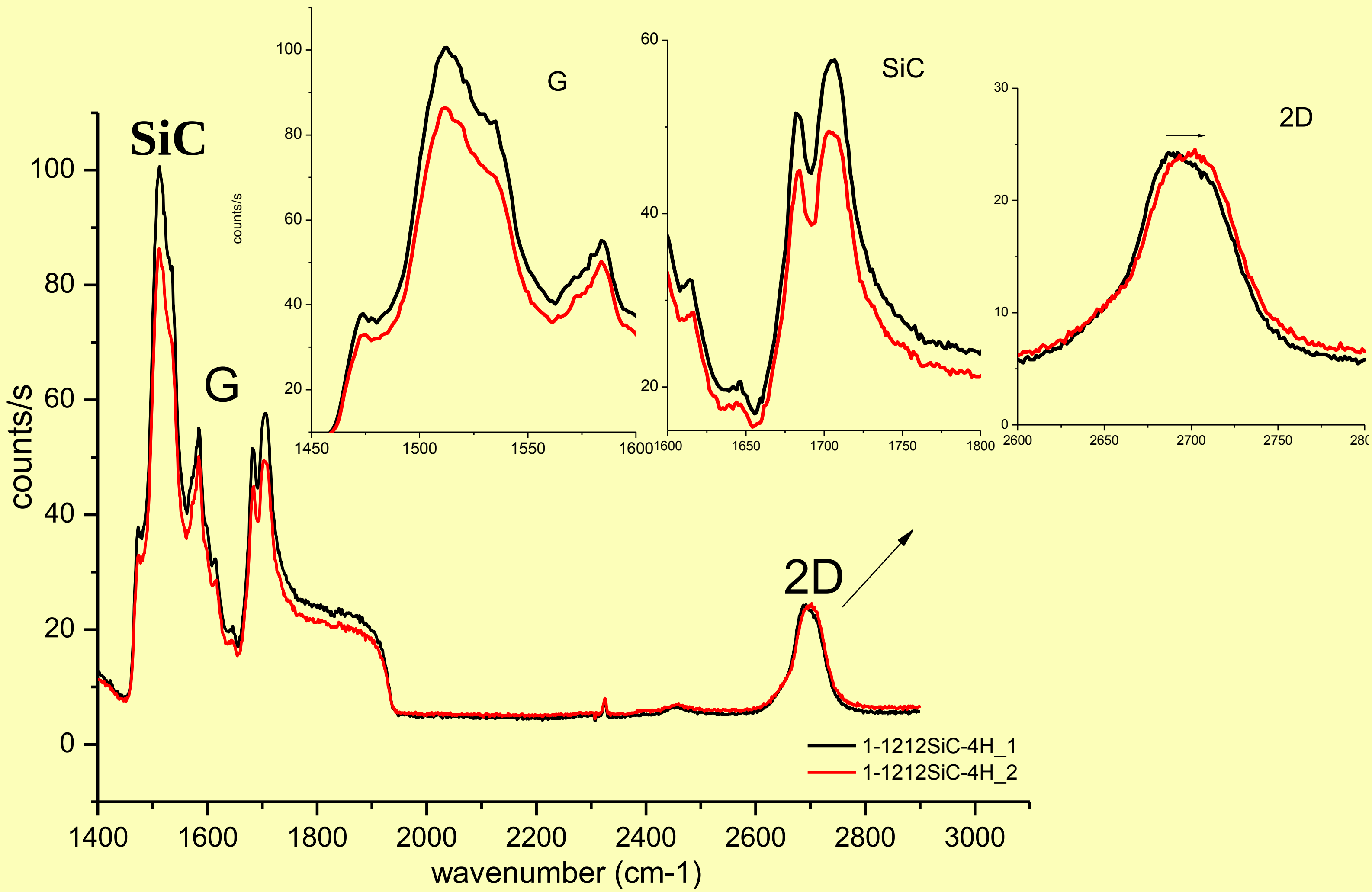
Epitaxial Graphene on SiC

- **Produced by sublimating Si from SiC heated up to high temperatures (round 1600°C)**
- **Enables processing on single 2", 3" and 4" wafers**
- **Homogenous, highly uniform deposition**



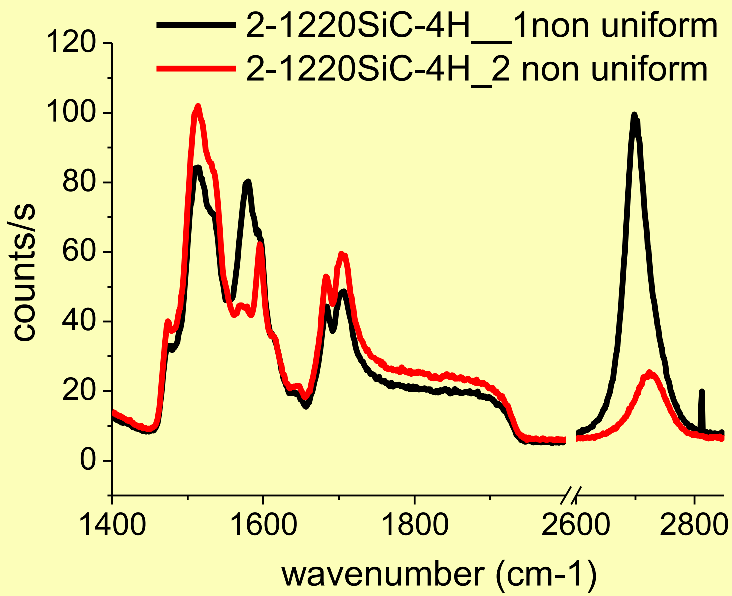
W. Strupinski et al., Nano Lett. **11**, (2011).

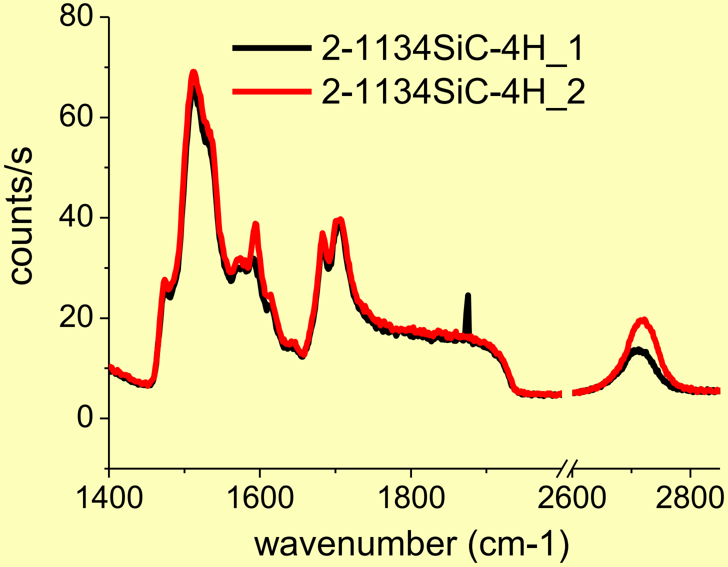
Raman measurements from different regions of the sample

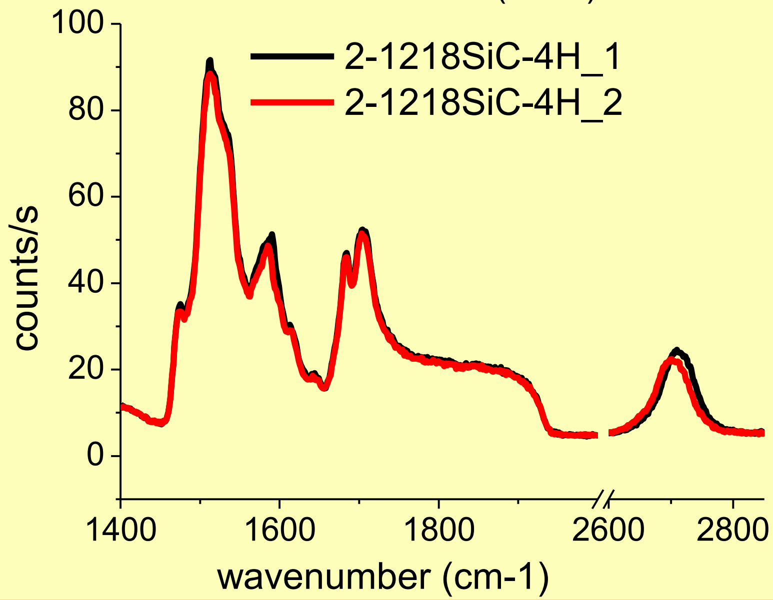


2D and G peaks shift, but there is no shift in SiC peak.

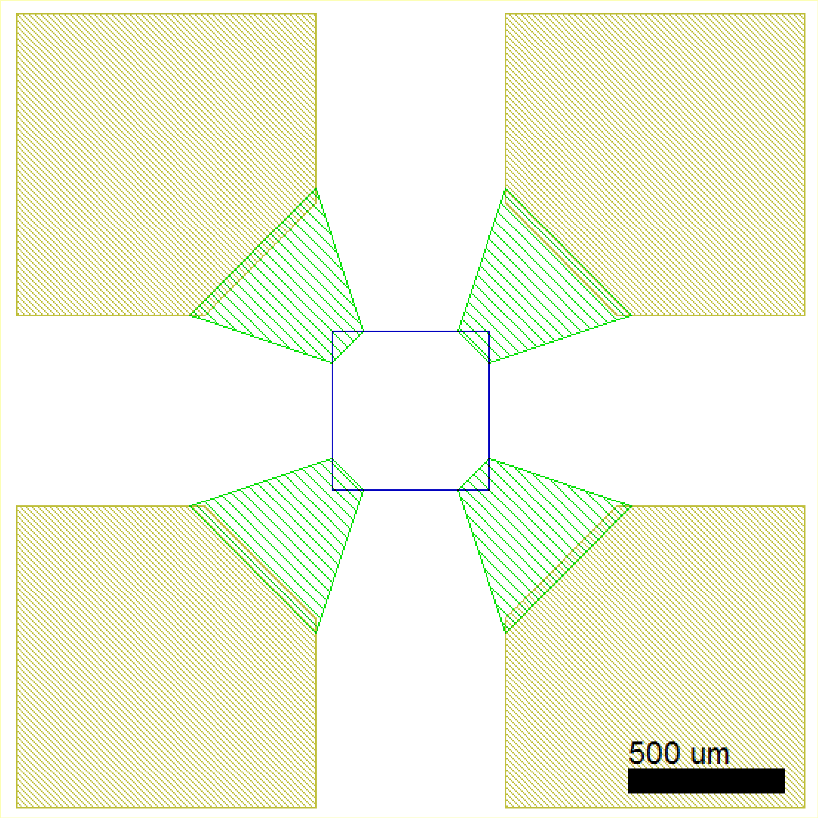
Raman measurements

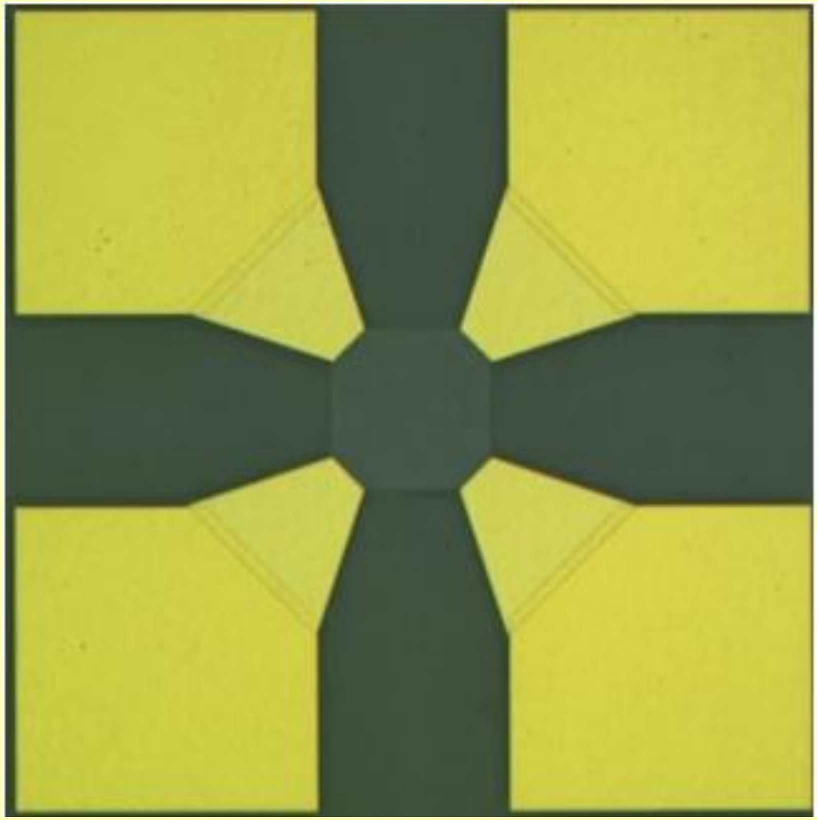






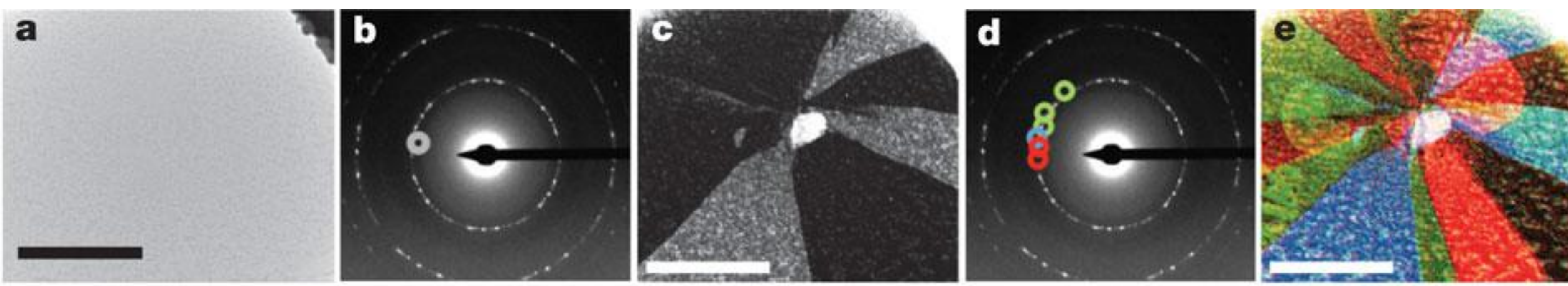
Van der Pauw Devices for Hall Measurements





Hall Measurement Results at Room Temperature

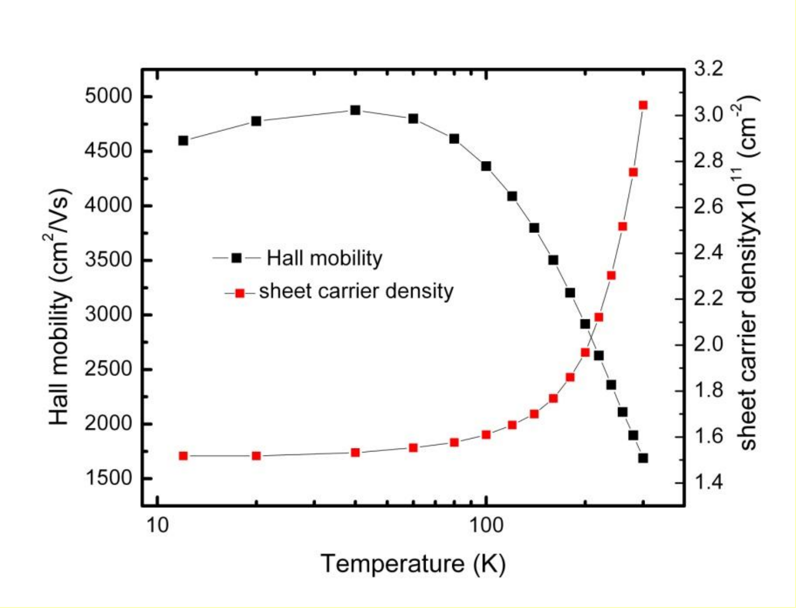
Sample Name	Growth Conditions	Device Number	μ (cm^2/Vs)	n (10^{12} cm^{-2})	Probe current (μA)
AaEk	1600°C	1	812,0	-1,7	100
		2	882,0	-1,5	500
		average	847,0	-1,6	
AbEk	1600°C + H_2	1	456,0	-6,3	100
		2	541,0	-3,6	100
		average	498,5	-5,0	
BaEk	1500°C	1	1580,0	23,0	1000
		2	1026,0	30,5	1000
		average	1303,0	26,8	
BbEk	1500°C + H_2	1	873,0	-1,5	500
		2	1350,0	-0,7	500
		average	1111,5	-1,1	



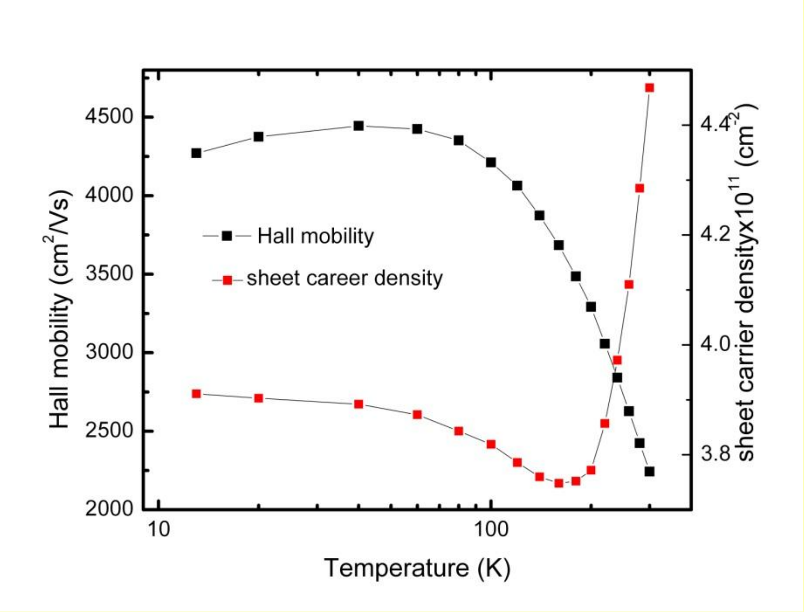
Huang et al. Nature **469**, (2011).

Linköping Samples Temperature dependent Mobility and Sheet Concentration

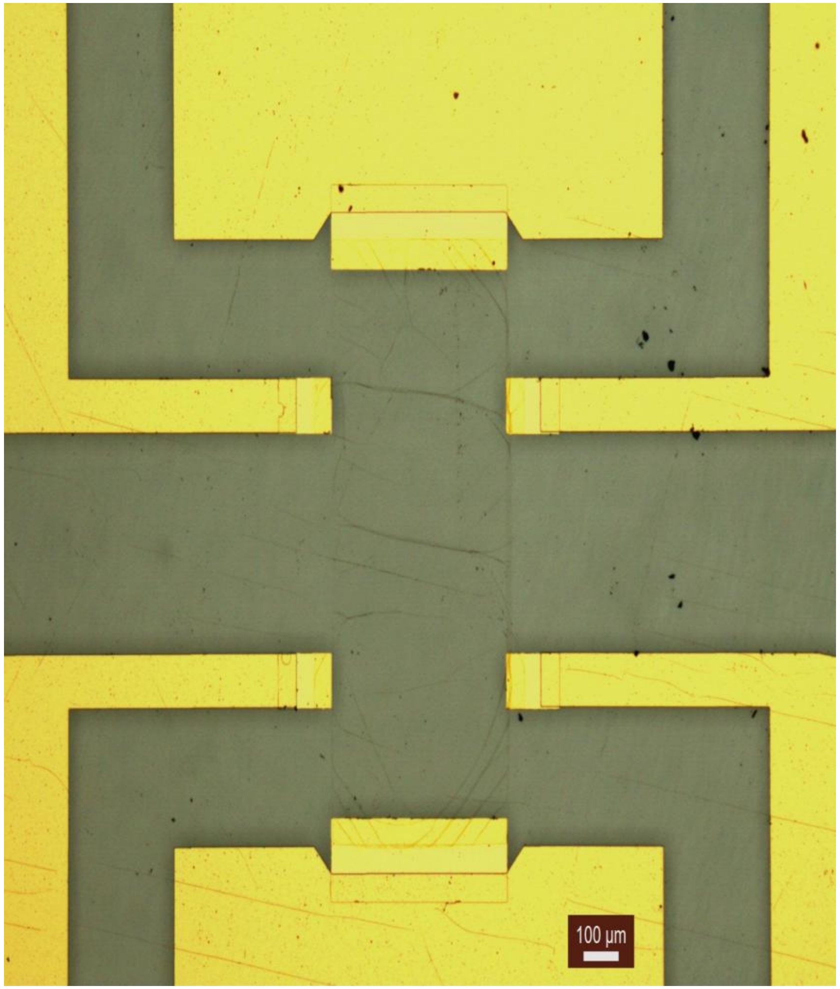
X573a Low Temperature

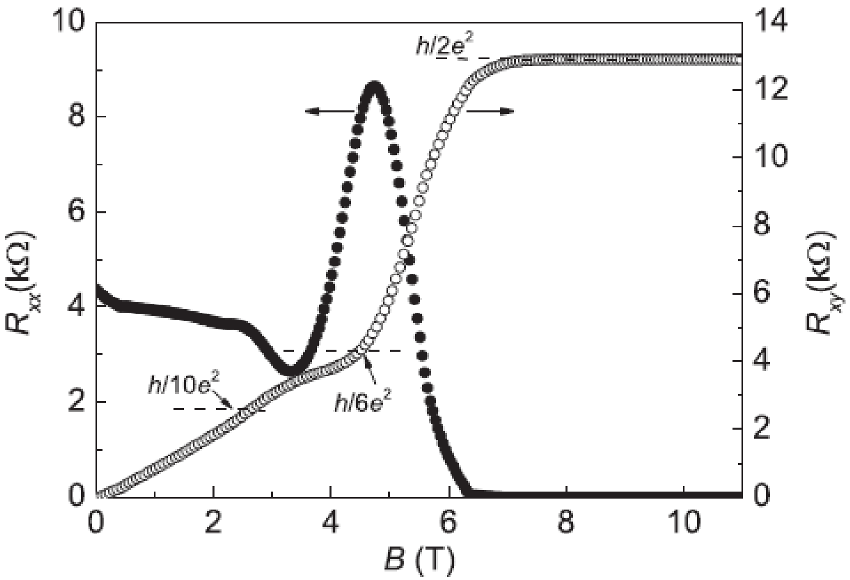


X575a Low Temperature



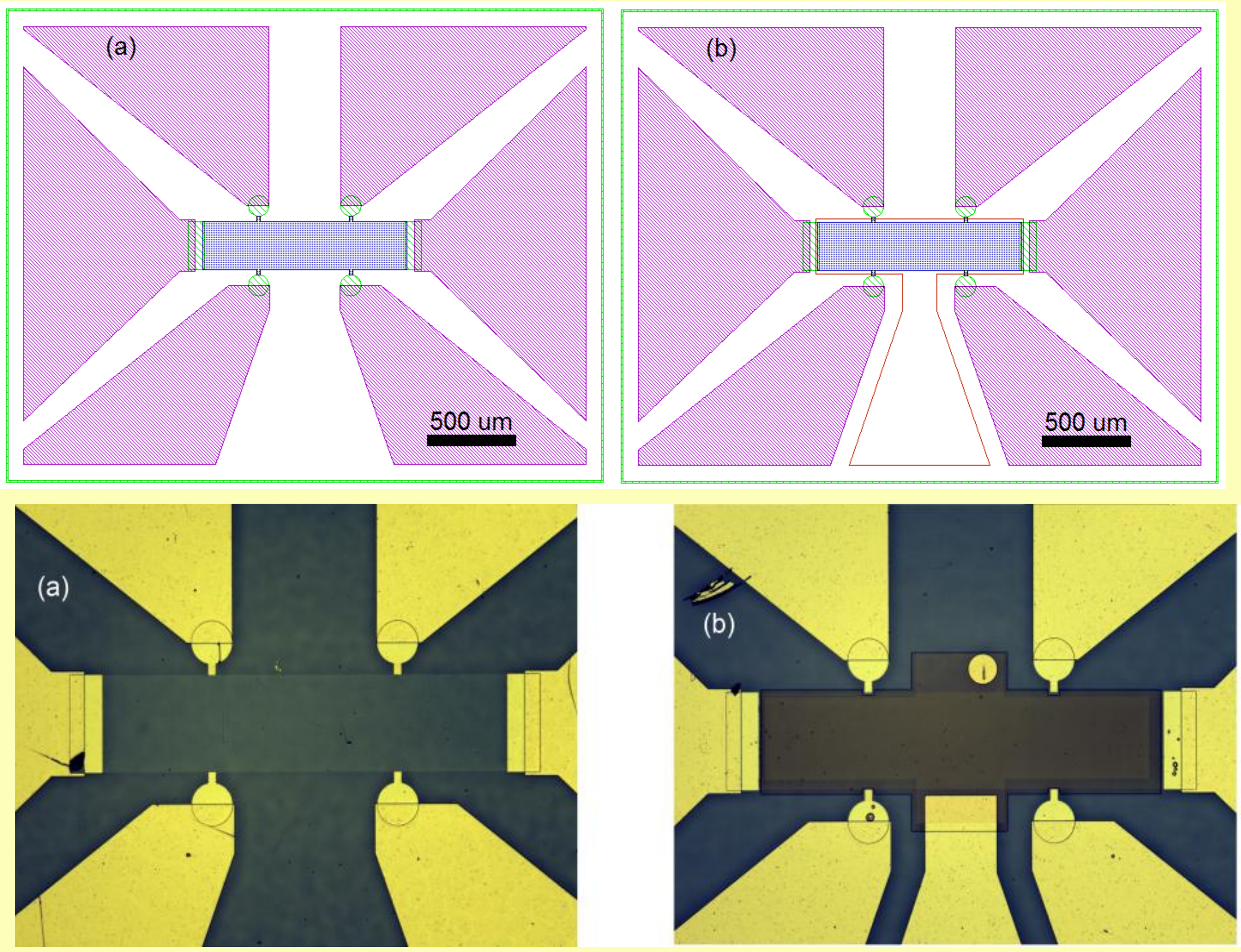
Hall Bar Fabrication for Magnetoresistance Measurements



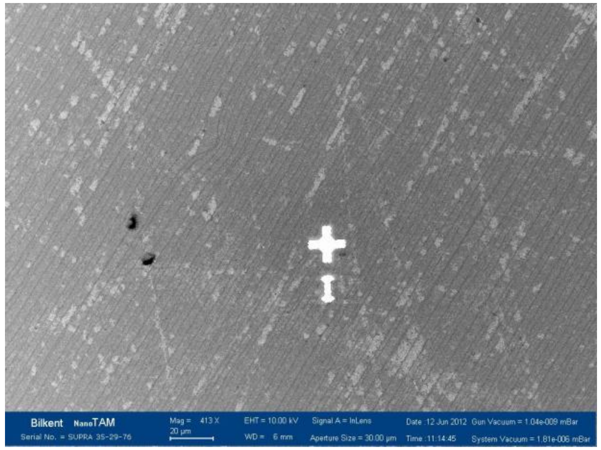


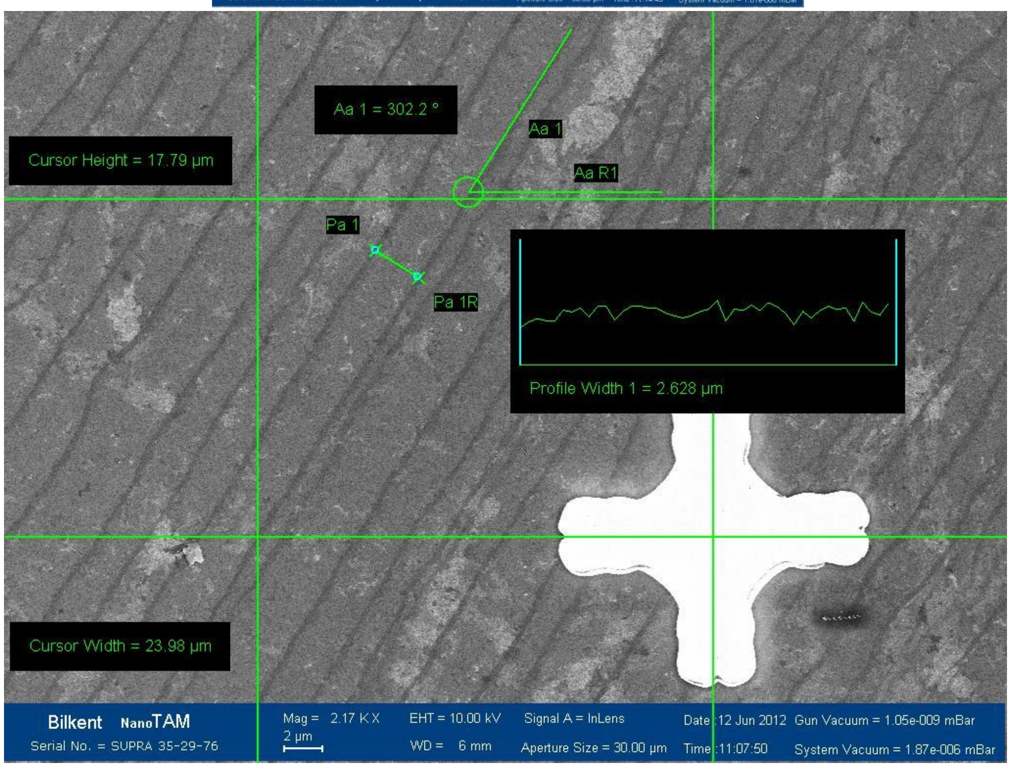
E. Tiras et al. , JAP **113**, (2013).

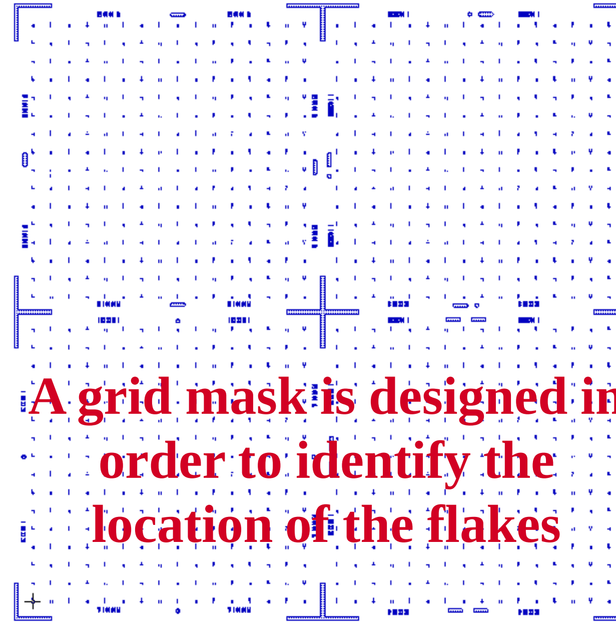
Hall Transistor Fabrication



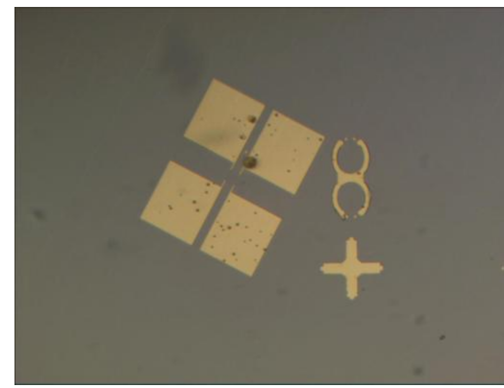
Micro Hall Bars

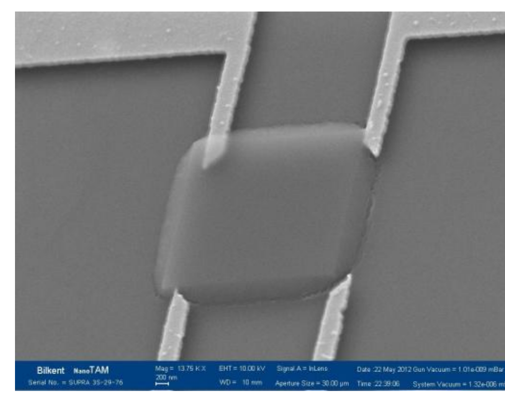






A grid mask is designed in order to identify the location of the flakes





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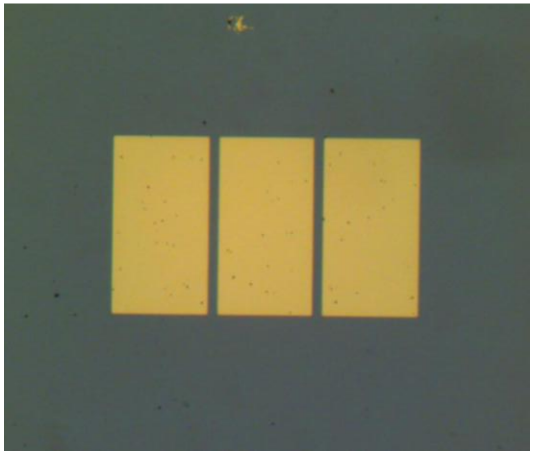
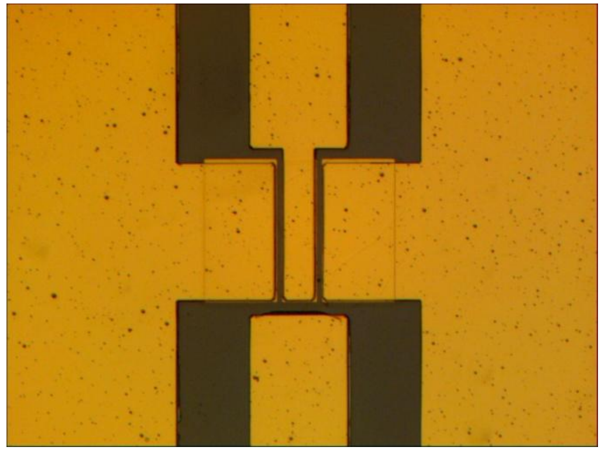
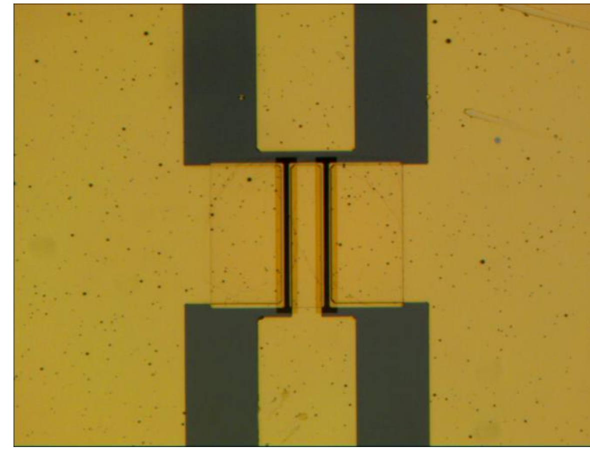
RF Transistor Fabrication Steps



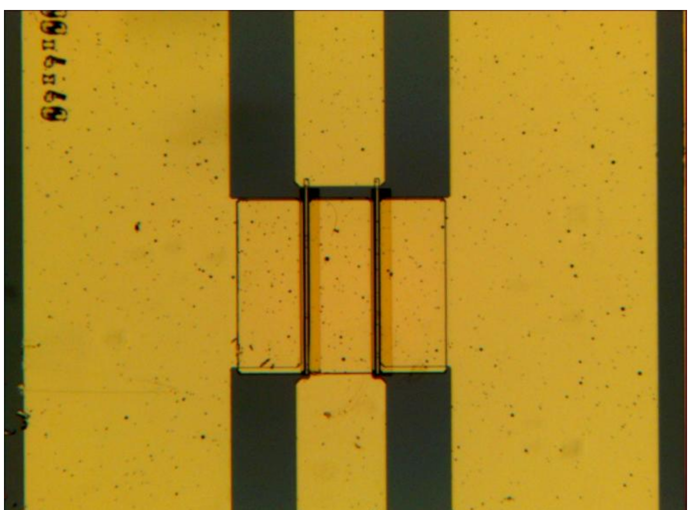
Ohmic contacts

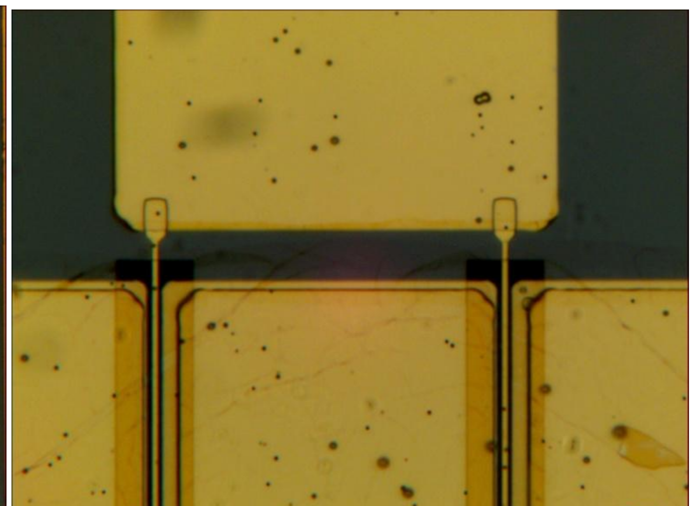


Interconnect metals

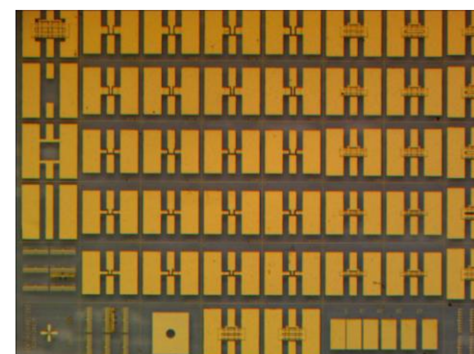


Passivation of active region with SiO_2

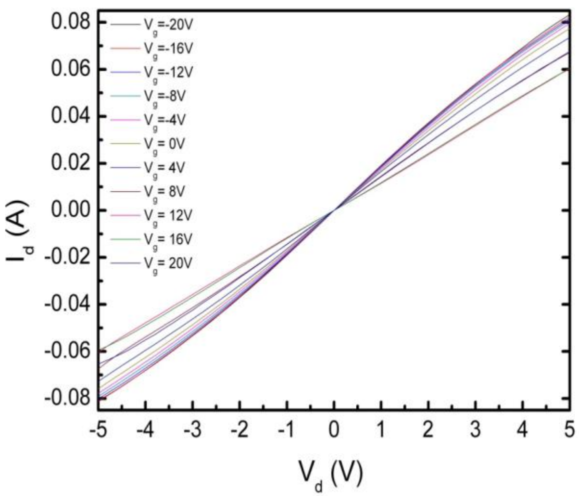


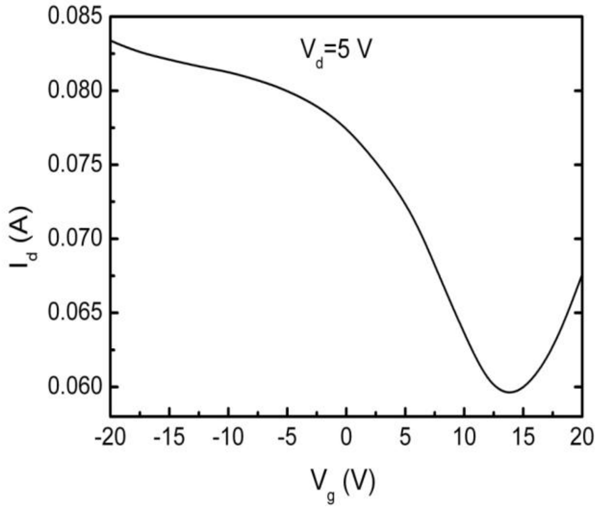


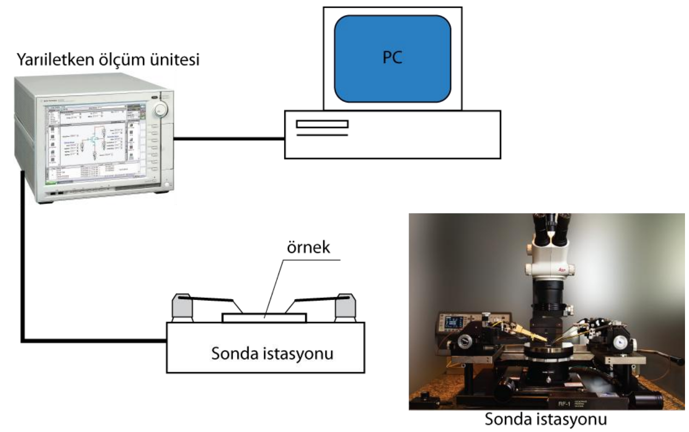
Gates

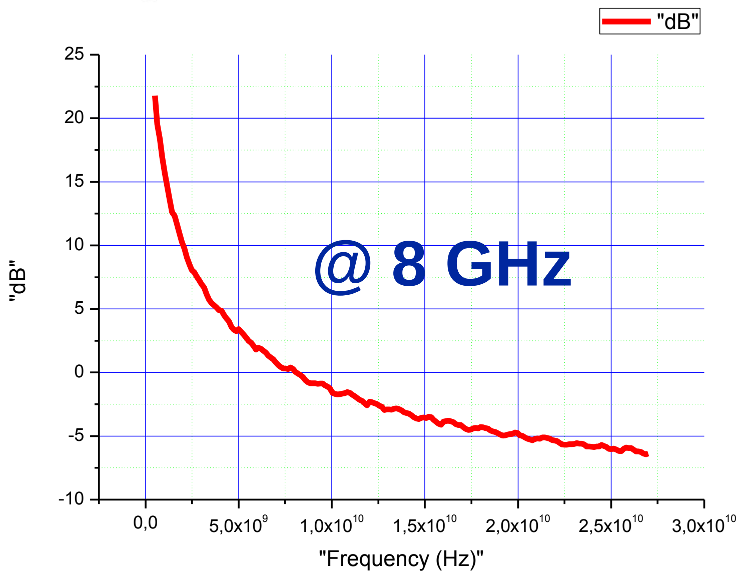


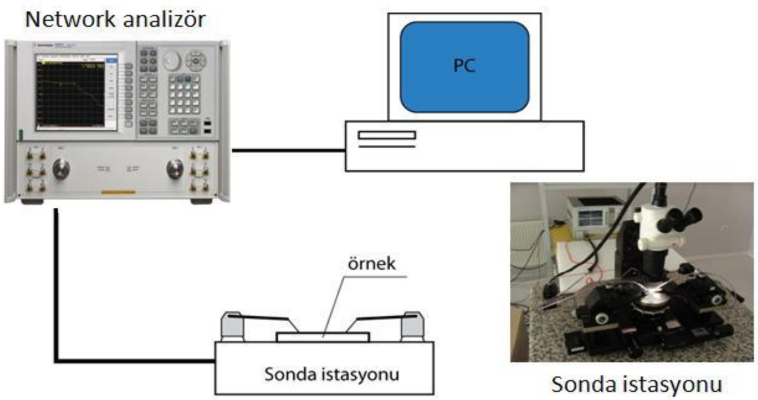
Transistor Measurents











$$H_{21} = \frac{-2 \cdot S_{21}}{(1 - S_{11}) \cdot (1 + S_{22}) + S_{12} \cdot S_{21}}$$

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nature photonics

FOCUS | REVIEW ARTICLES

PUBLISHED ONLINE: 31 OCTOBER 2012 | DOI: 10.1038/NPHOTON.2012.262

Graphene plasmonics

A. N. Grigorenko[1*], M. Polini[2] and K. S. Novoselov[1]

Two rich and vibrant fields of investigation—graphene physics and plasmonics—strongly overlap. Not only does graphene possess intrinsic plasmons that are tunable and adjustable, but a combination of graphene with noble-metal nanostructures promises a variety of exciting applications for conventional plasmonics. The versatility of graphene means that graphene-based plasmonics may enable the manufacture of novel optical devices working in different frequency ranges—from terahertz to the visible—with extremely high speed, low driving voltage, low power consumption and compact sizes. Here we review the field emerging at the intersection of graphene physics and plasmonics.

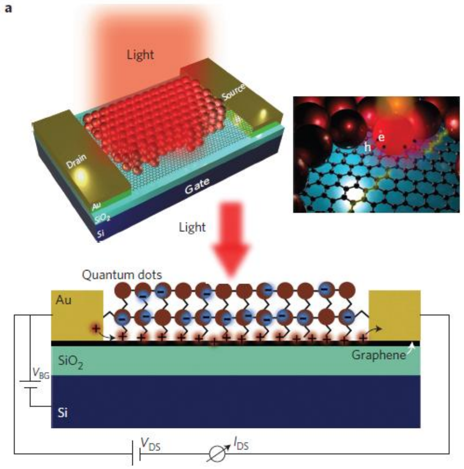
nature nanotechnology

LETTERS

PUBLISHED ONLINE: 6 MAY 2012 | DOI: 10.1038/NNANO.2012.60

Hybrid graphene–quantum dot phototransistors with ultrahigh gain

Gerasimos Konstantatos†*, Michela Badioli, Louis Gaudreau, Johann Osmond, Maria Bernechea, F. Pelayo Garcia de Arquer, Fabio Gatti and Frank H. L. Koppens†*



NANO LETTERS

Letter

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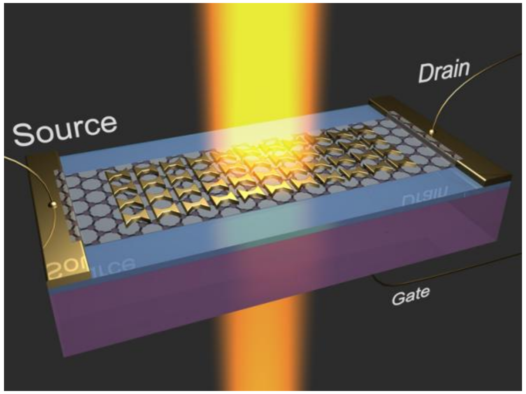
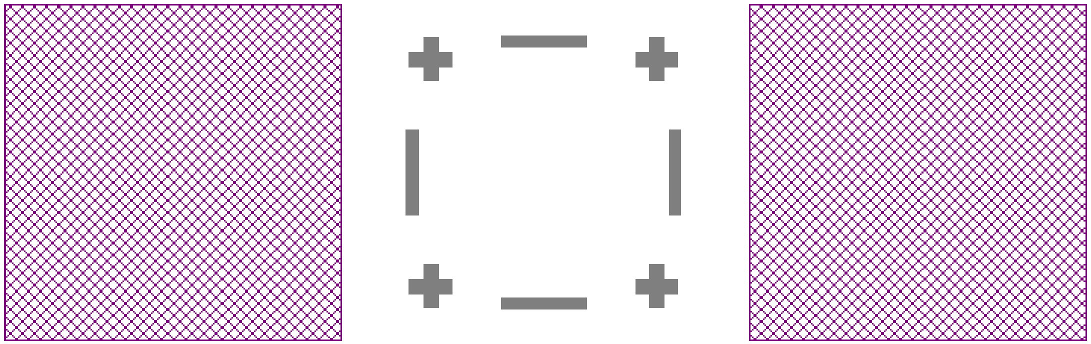
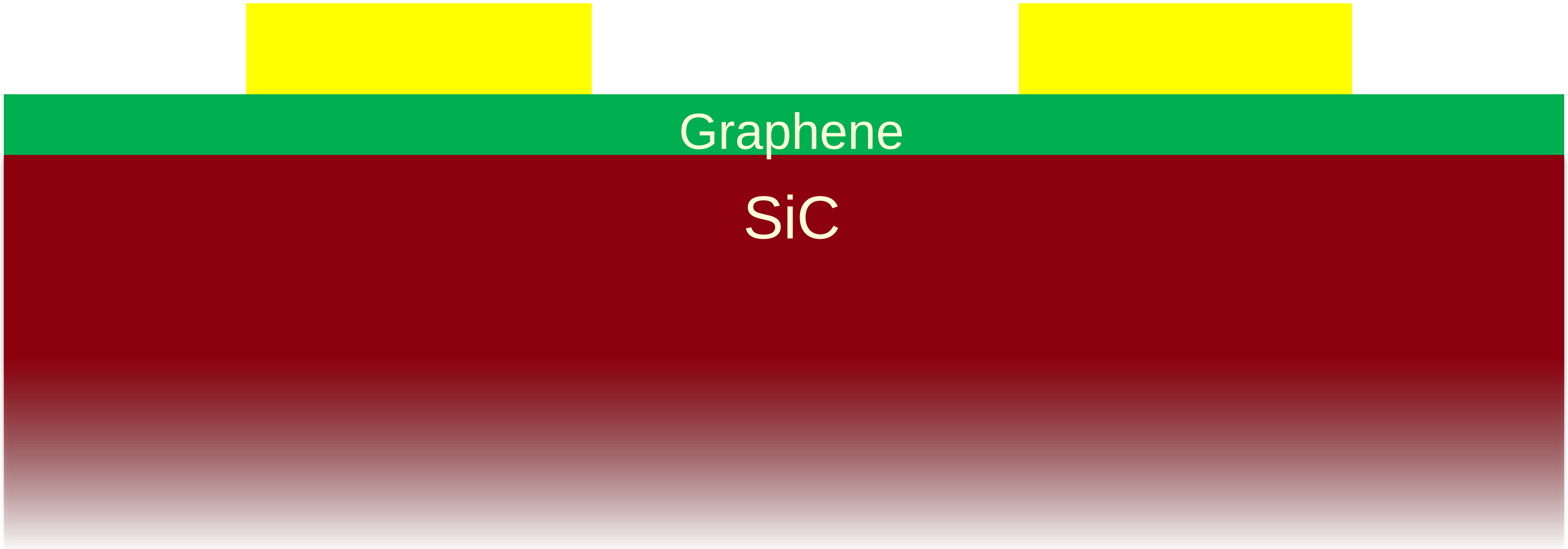
Electrically Tunable Damping of Plasmonic Resonances with Graphene

Naresh K. Emani,[†,§] Ting-Fung Chung,[‡,§] Xingjie Ni,[†,§] Alexander V. Kildishev,[†,§] Yong P. Chen,[‡,†,§] and Alexandra Boltasseva[*,†,§,||]

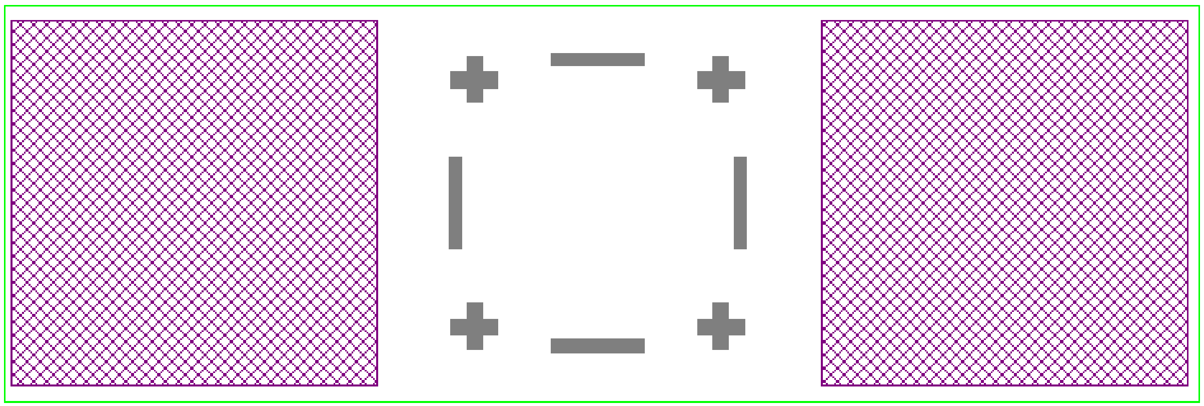


Ohmic Contacts and Alignment Marks





Mesa Etching of the Active Region



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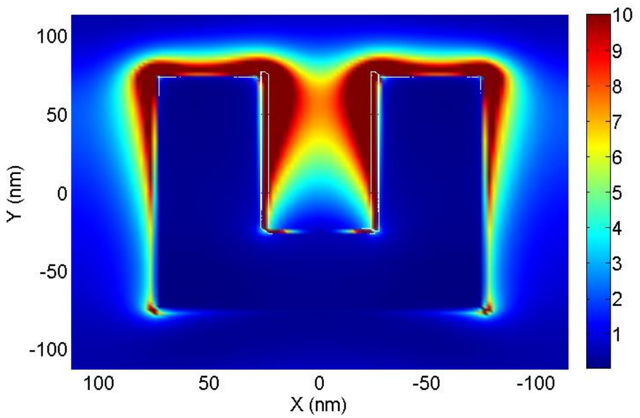
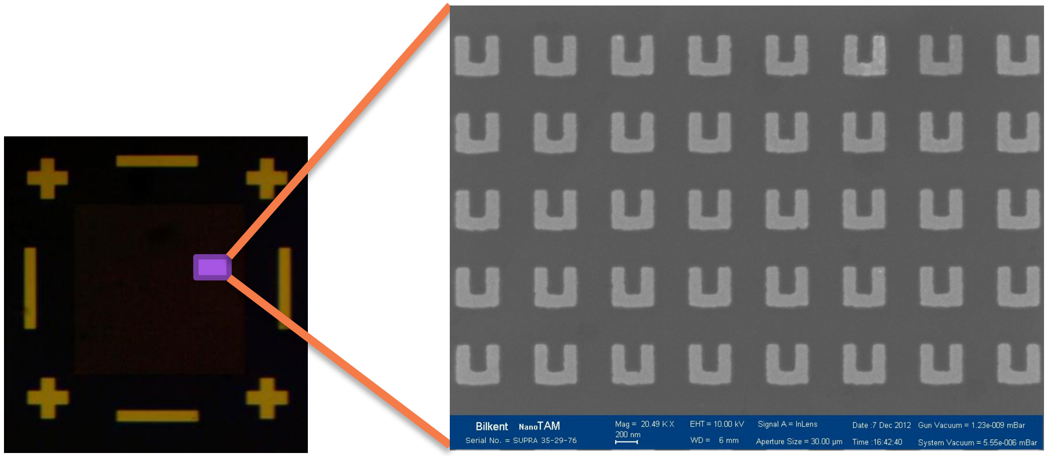
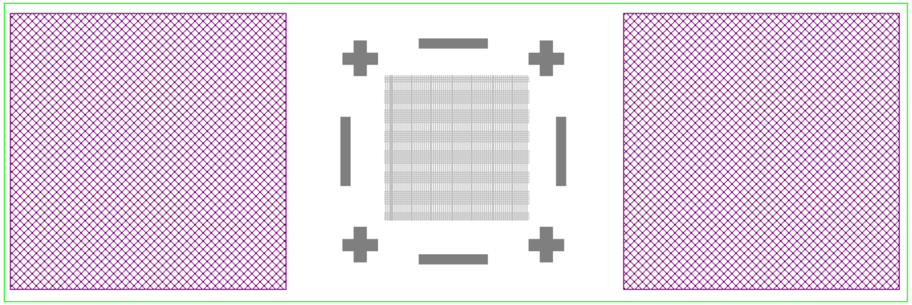
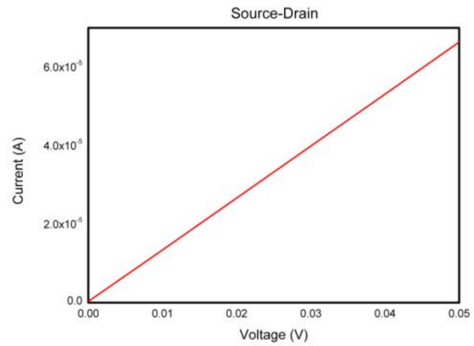
SRR Fabrication

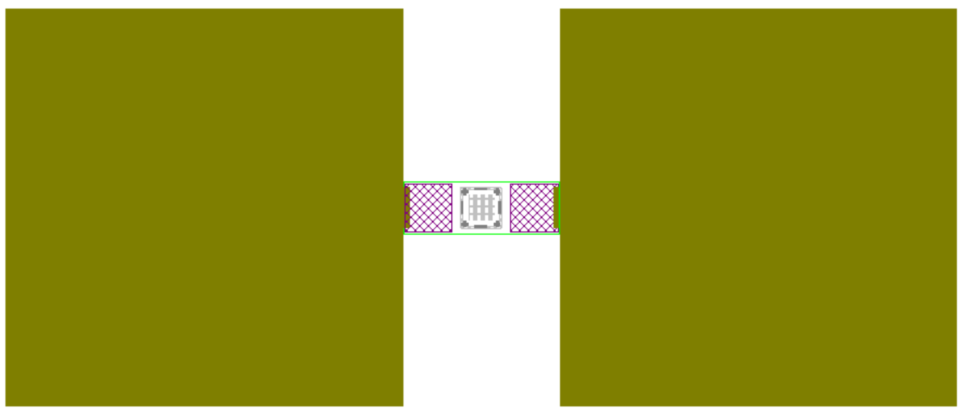


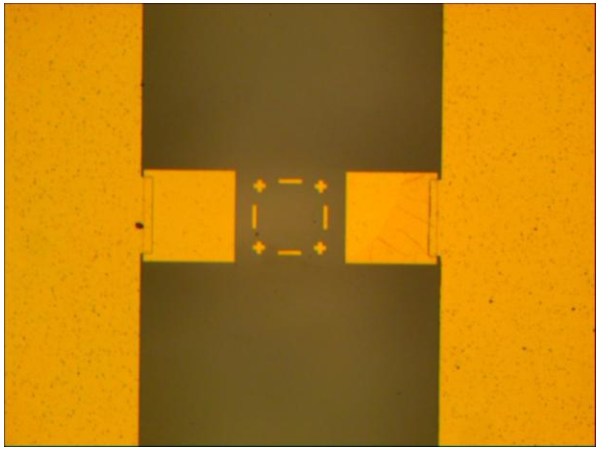


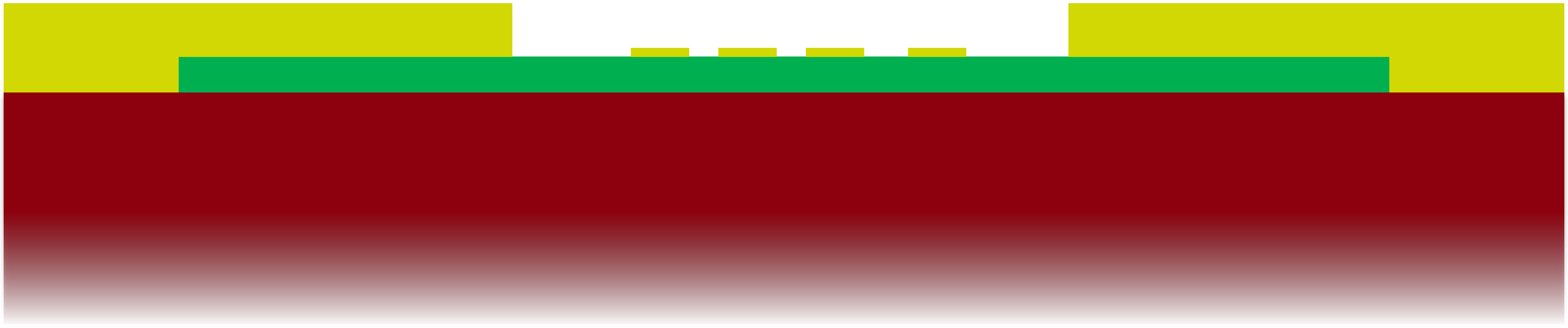


Interconnect Metallization





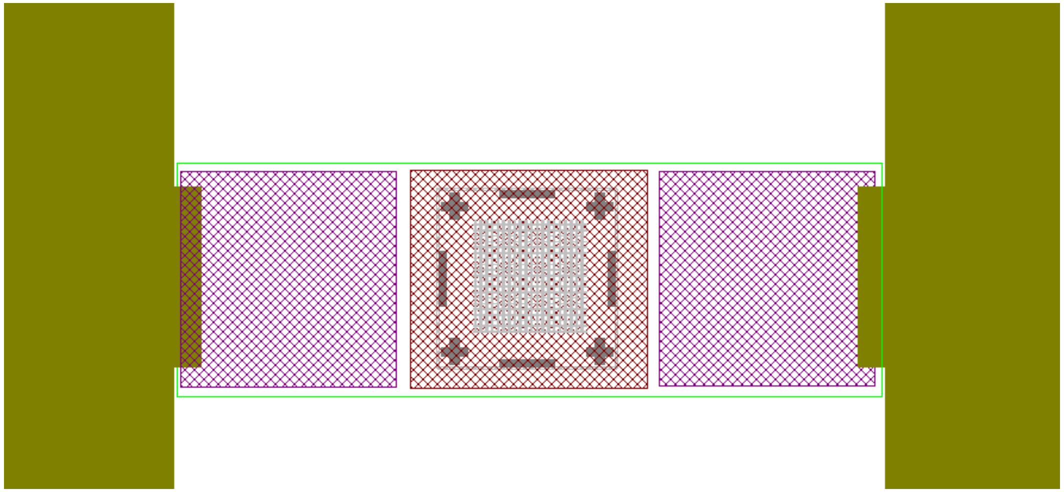


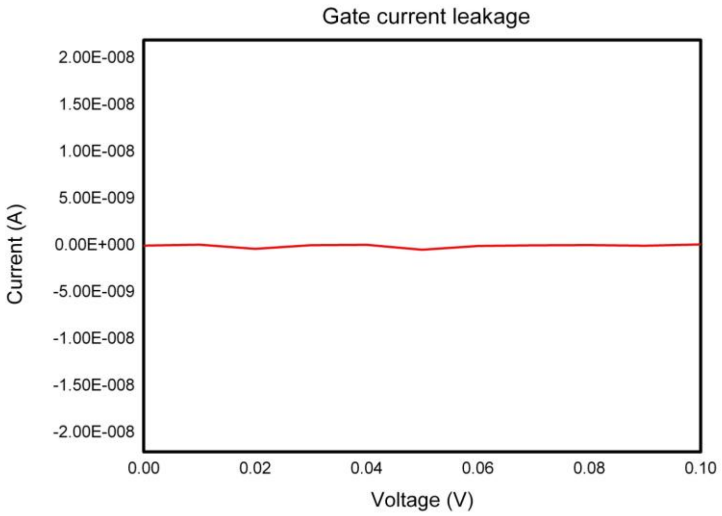


Dielectric Passivation

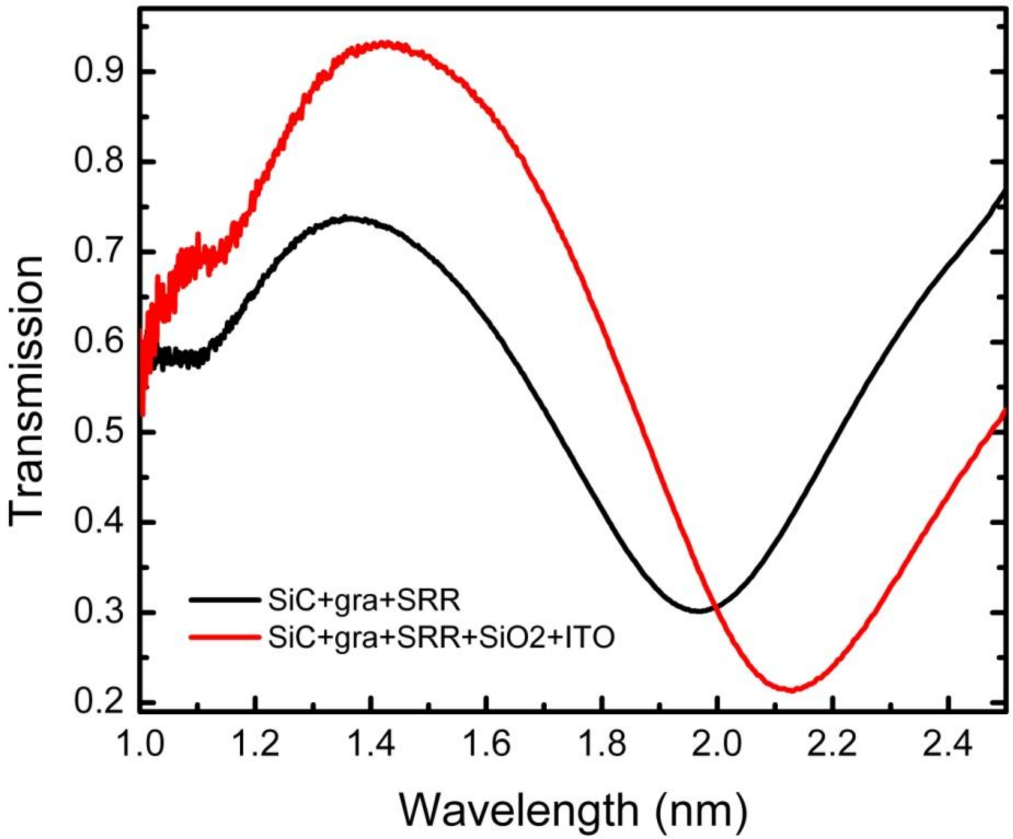
- 50 nm SiO_2 deposition with electron beam evaporation
- 50 nm SiO_2 deposition with sputter

ITO Deposition as a Gate

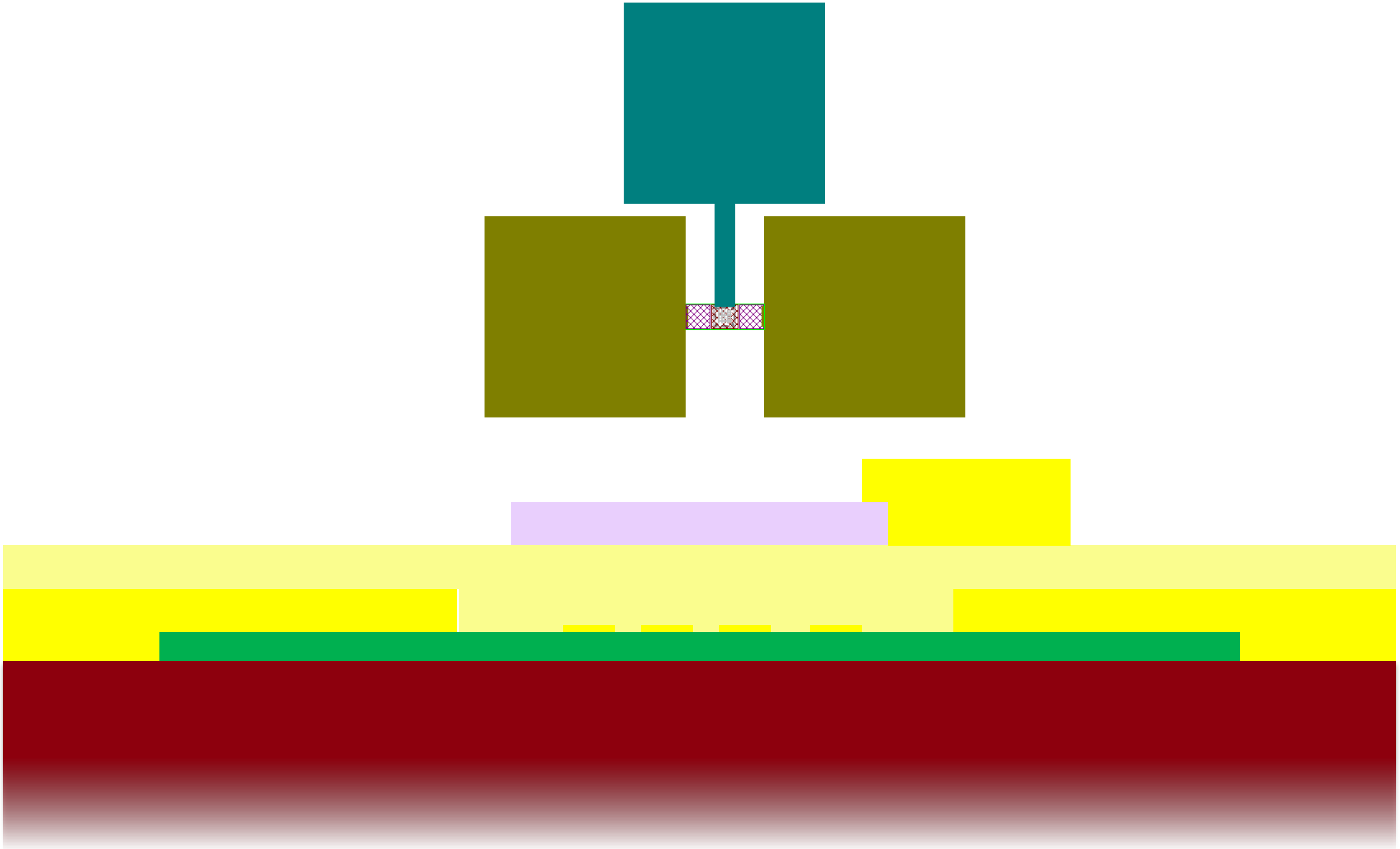




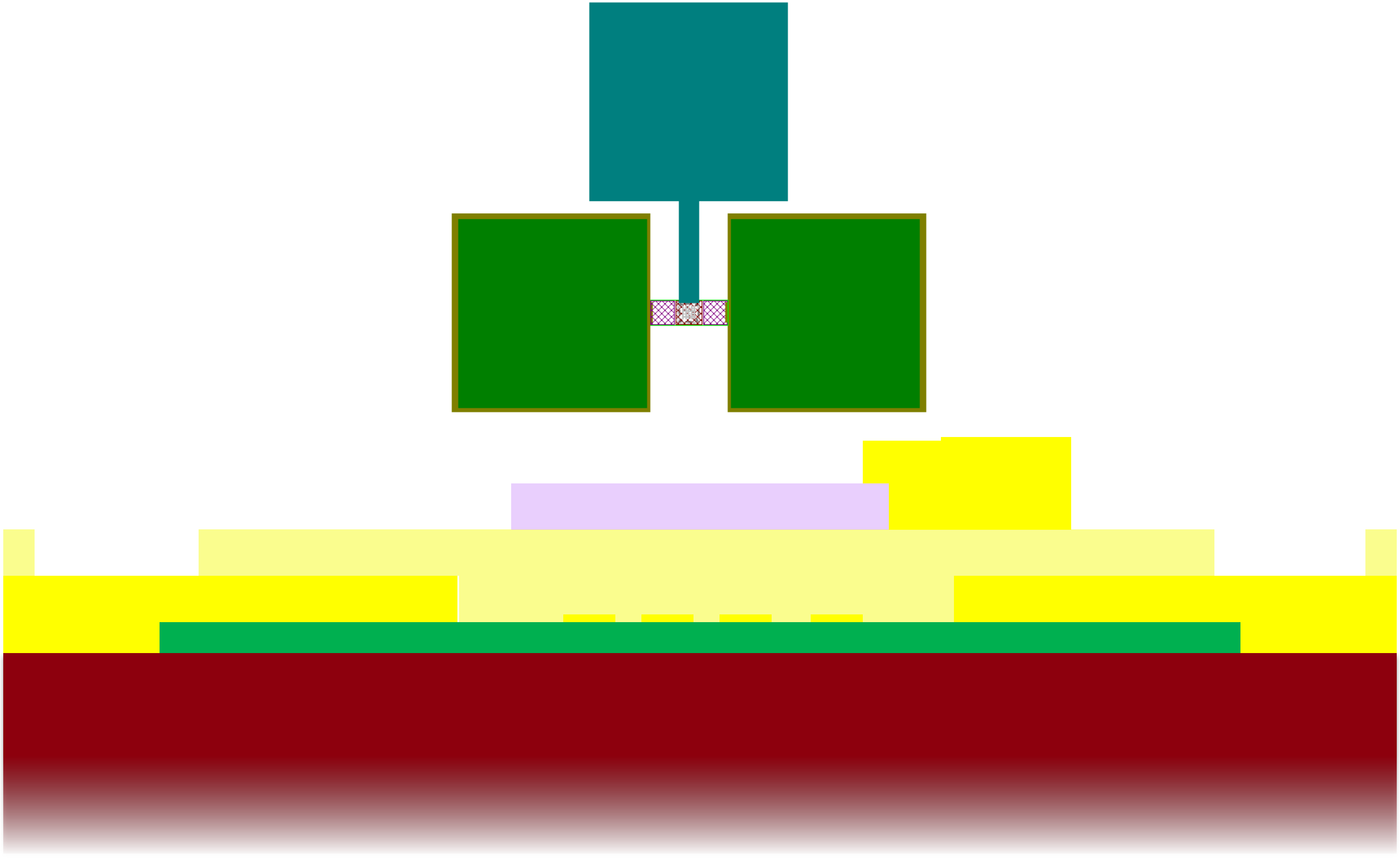
Effect of SiO_2 and ITO on the transmission



Gate Interconnect

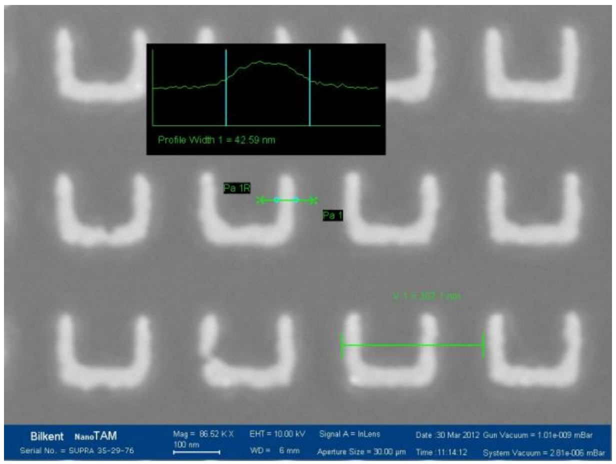


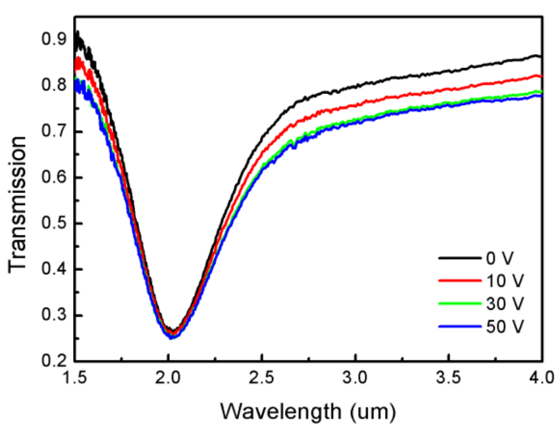
SiO_2 etching to reach the contacts



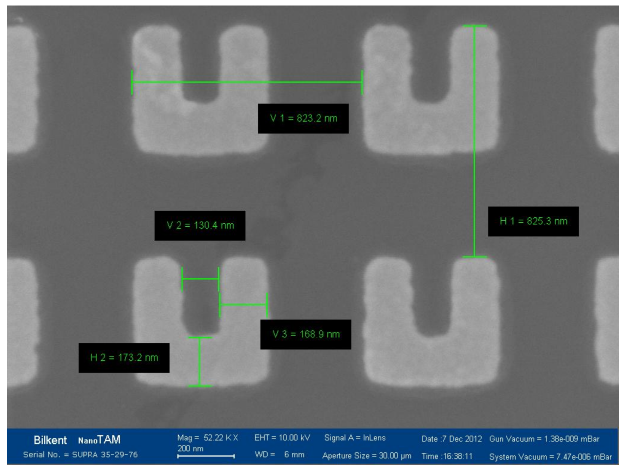
SRR Structures with Different Dimensions

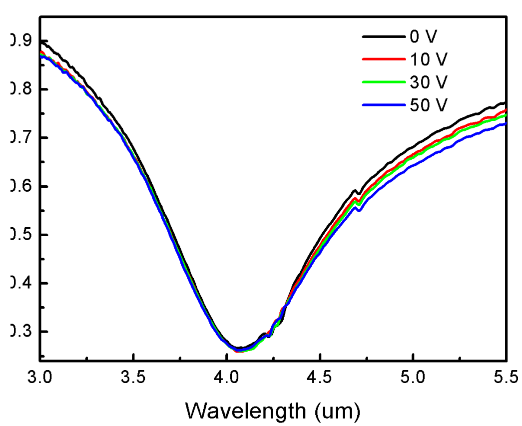
Device 1



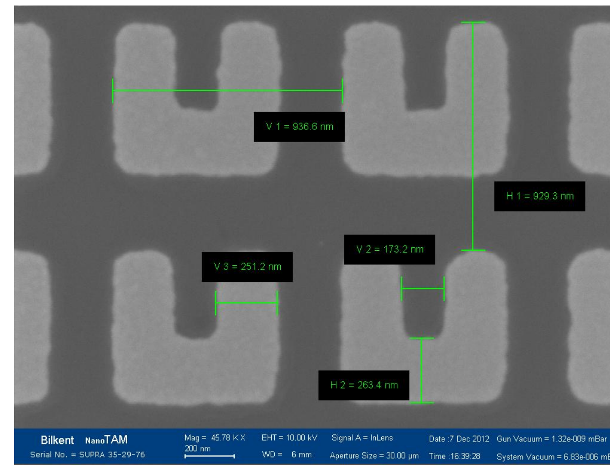


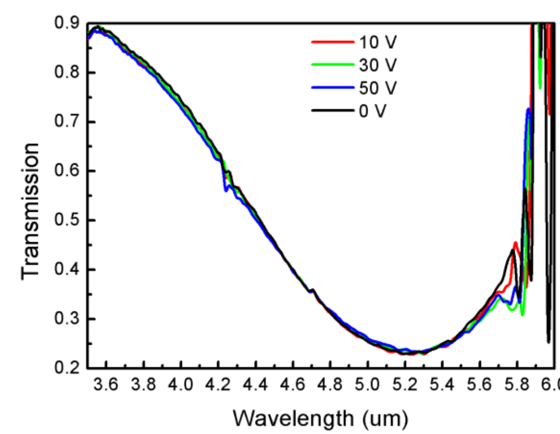
Device 2



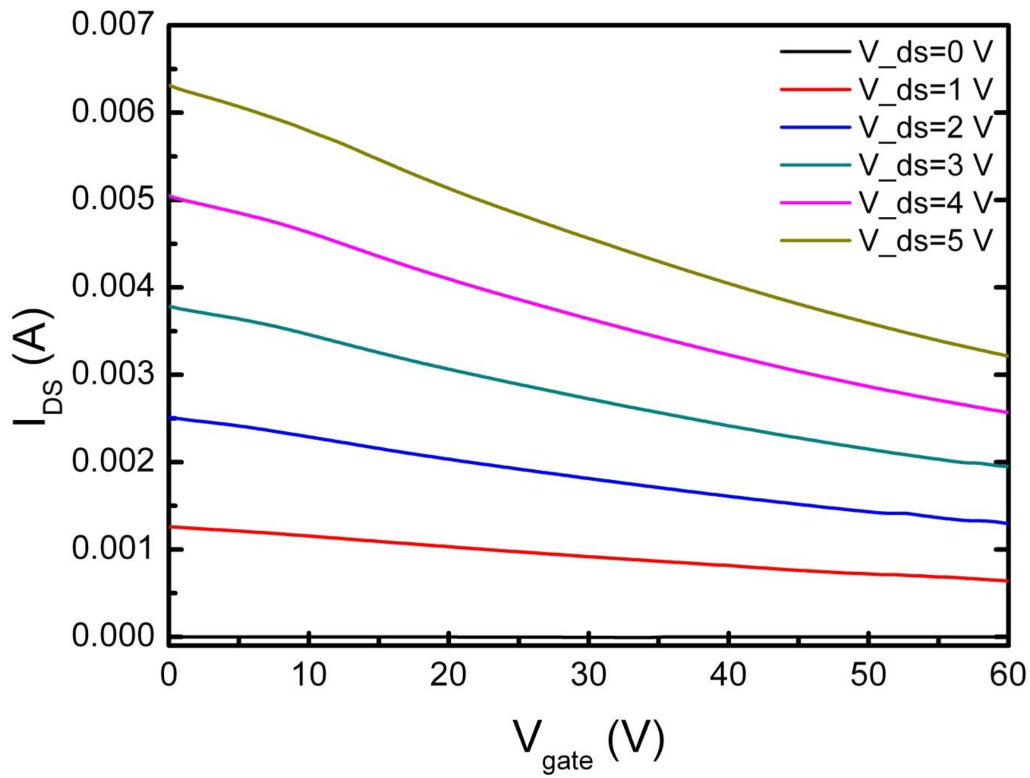


Device 3



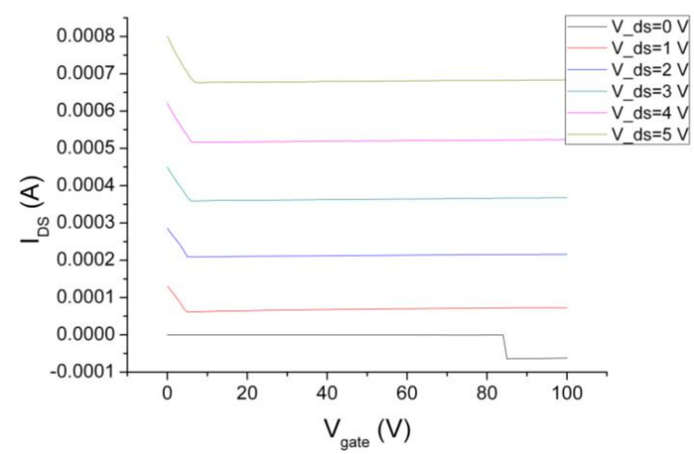


DC-IV Measurements of Plain Graphene

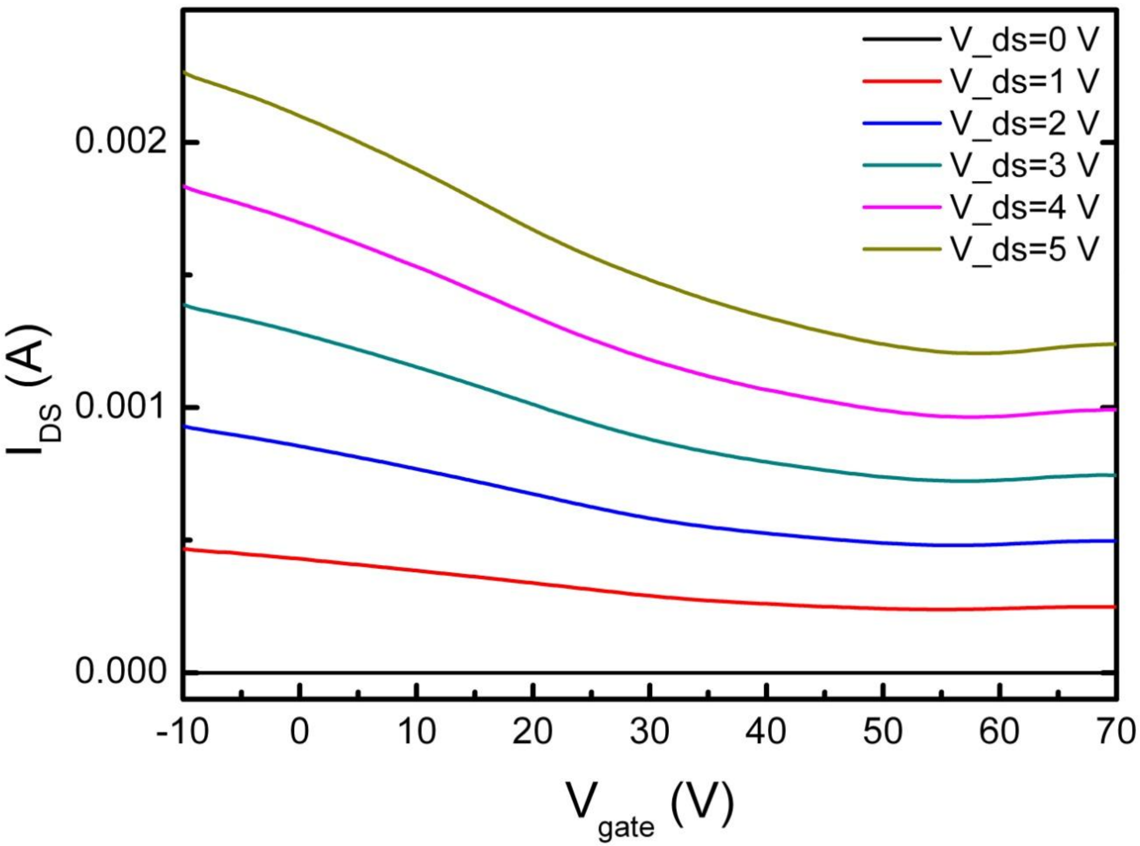


Dirac Point is larger than 60 V.

-Oxide layer breaks down instantaneously at 0.08-0.11 V per Angstrom thickness.
- This corresponds to 80-110 V for 100 nm SiO_2.

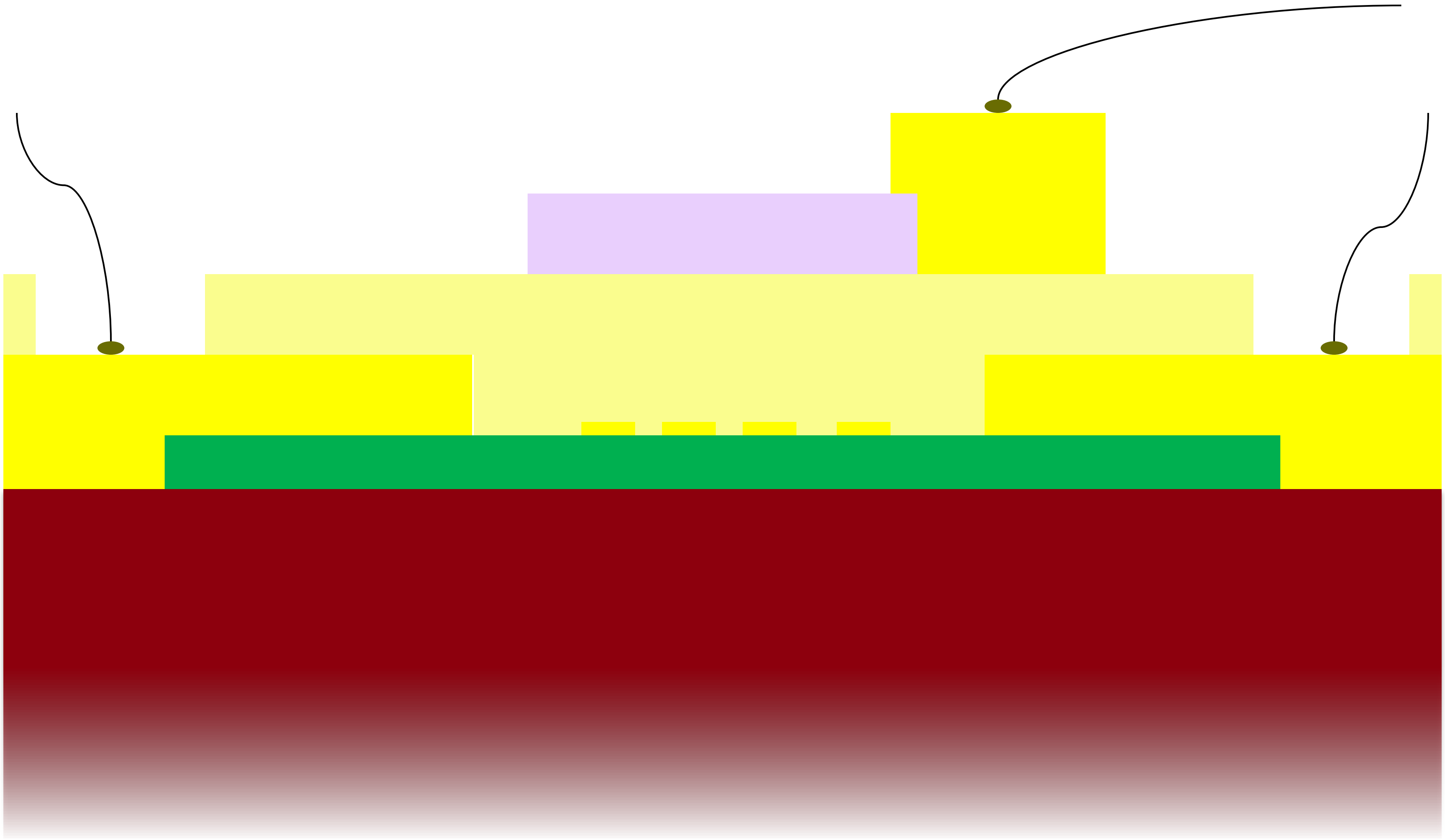


DC-IV Measurements of a Device with SRRs

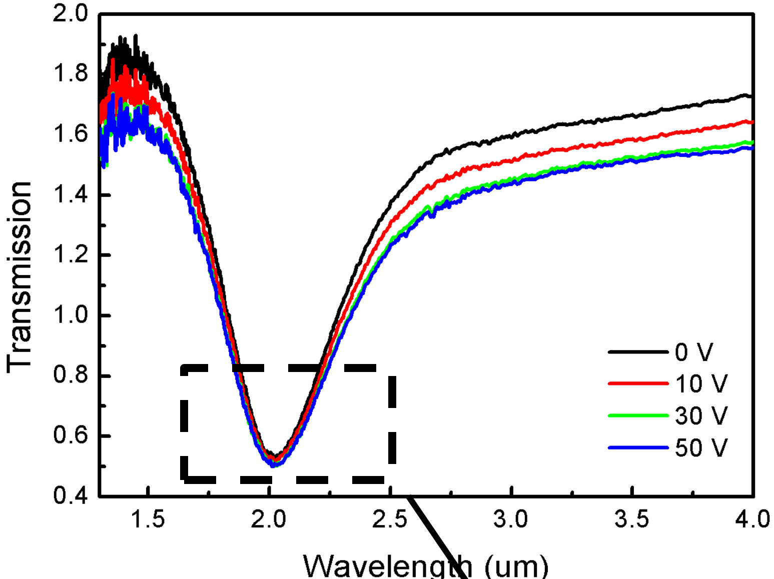


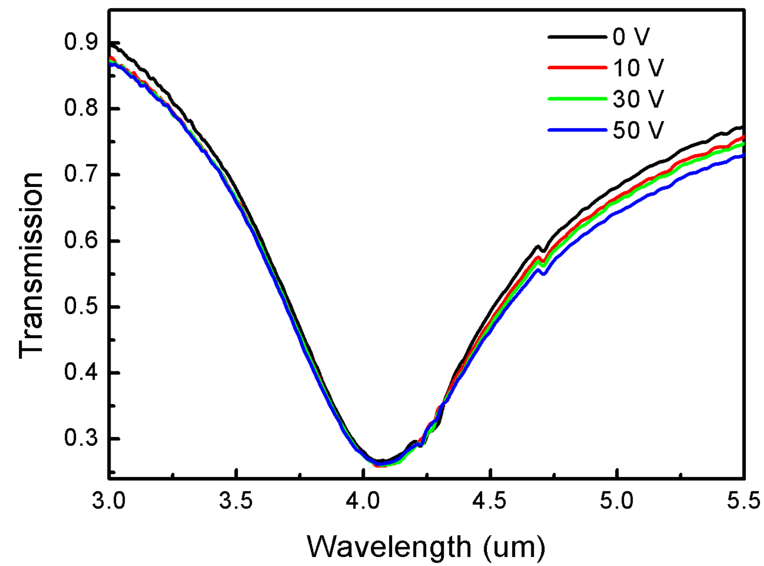
Dirac point is at 60 V.

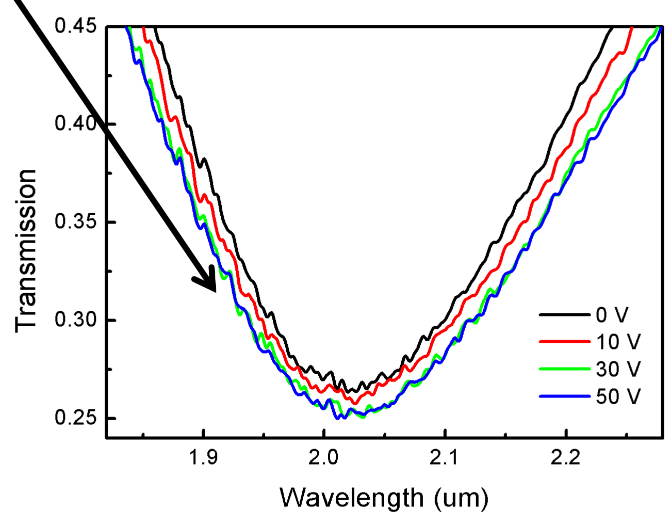
Bonding for the Transmission Measurements



Transmission Measurement Under Different Gate Bias







-Transmission decreases with applied gate voltage.
-The curve broadens asymmetrically.

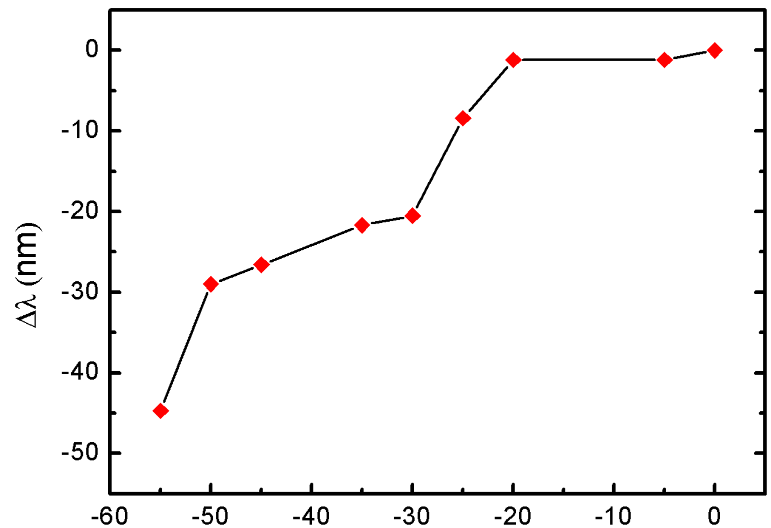
Device 1

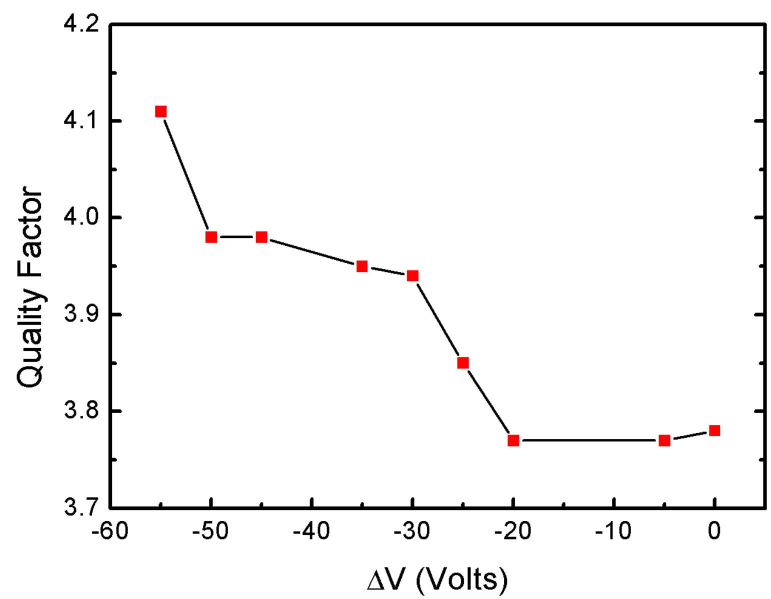
ΔV (V)	Δλ (nm)	Quality factor
0	0	3.78
-5	-1.2	3.77
-20	-1.2	3.77
-25	-8.4	3.85
-30	-20.5	3.94
-35	-21.7	3.95
-45	-26.6	3.98
-50	-29.0	3.98
-55	-44.7	4.11

$\Delta V = V_{gate} - V_{Dirac}$

Δλ is the line width difference

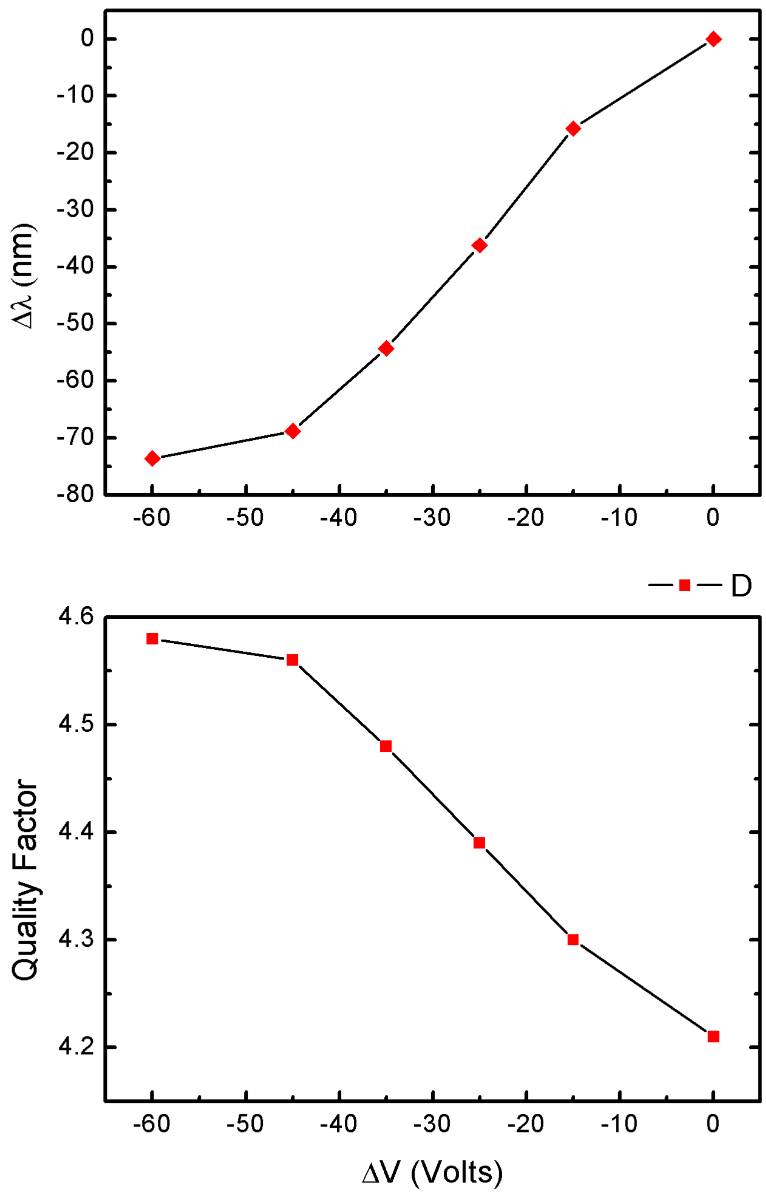
- Resonance dip broadens and quality factor decreases closer to Dirac point





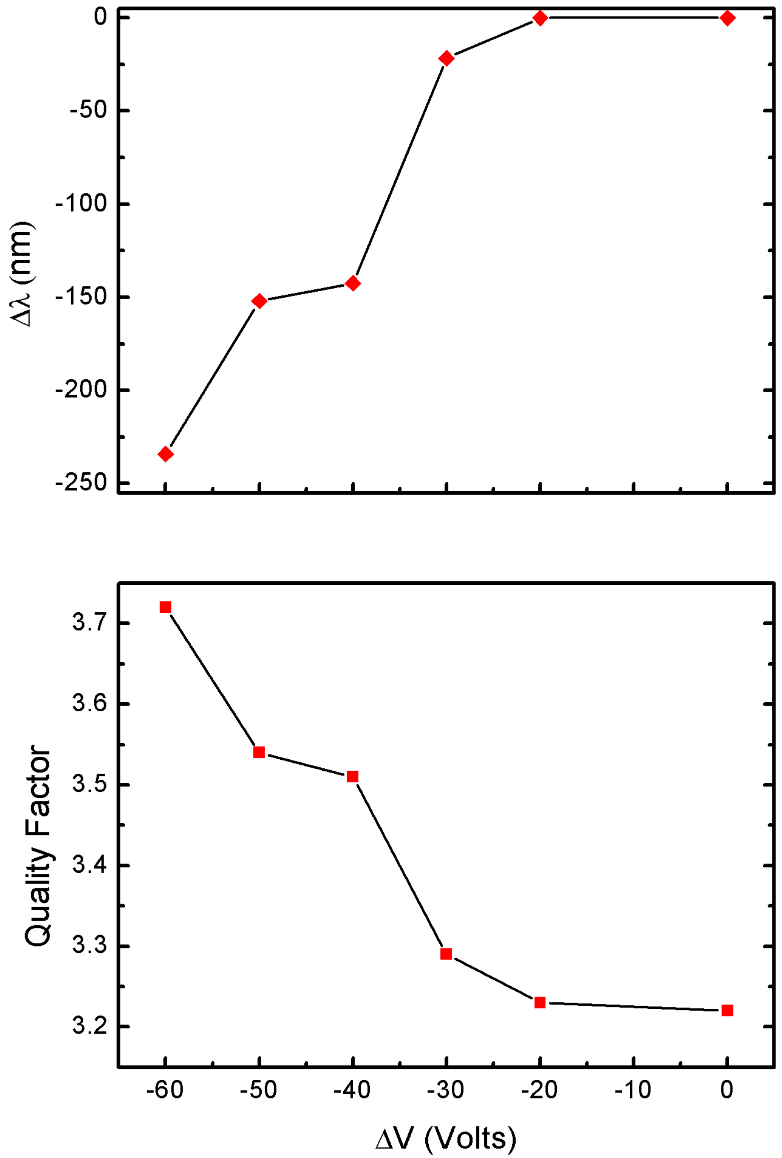
Device 2

ΔV (V)	Δλ (nm)	Quality Factor
0	0	4.21
-15	-15.7	4.30
-25	-36.2	4.39
-35	-54.3	4.48
-45	-68.8	4.56
-60	-73.6	4.58

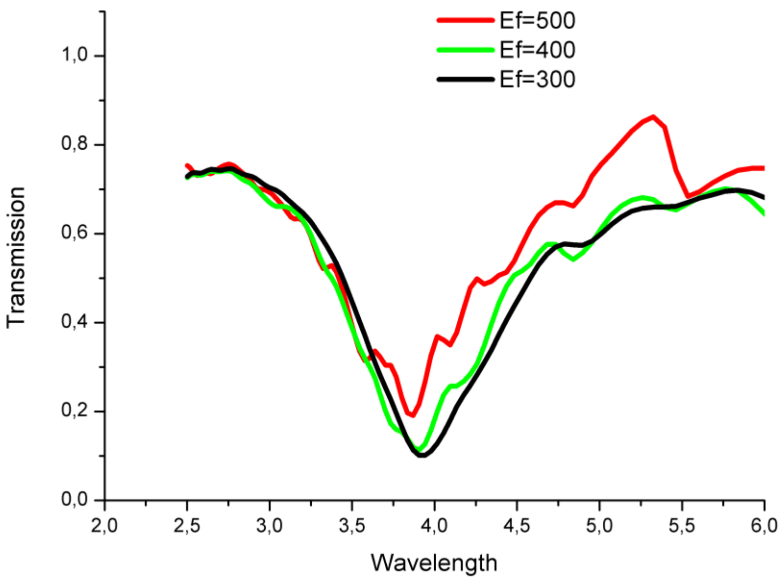


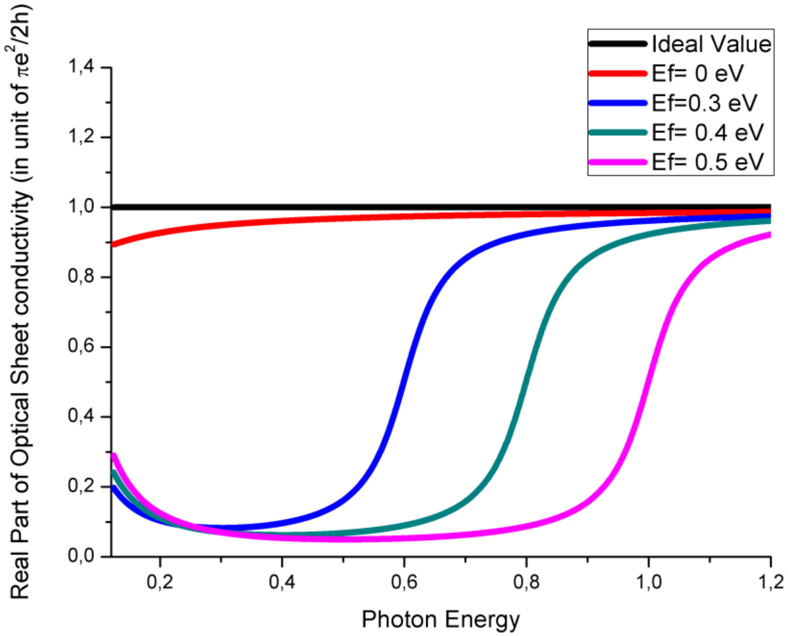
Device 3

ΔV (V)	Δλ (nm)	Quality Factor
0	0	3.22
-20	0	3.23
-30	-21.7	3.29
-40	-142.4	3.51
-50	-152.0	3.54
-60	-234.1	3.72



Theoretical Model for the Graphene



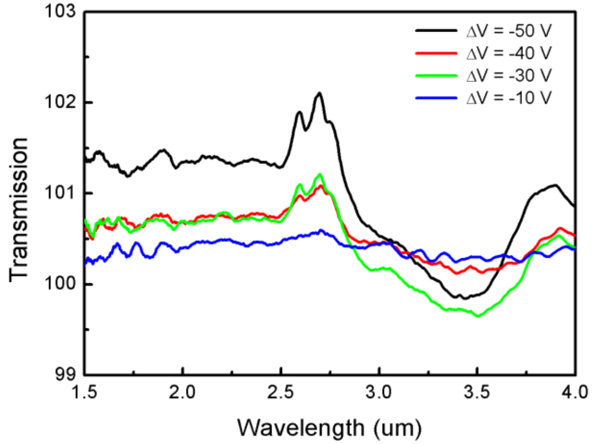


$n \approx 2*10^{13}\ cm^{-2}$

$E_F \approx 0.5$ eV

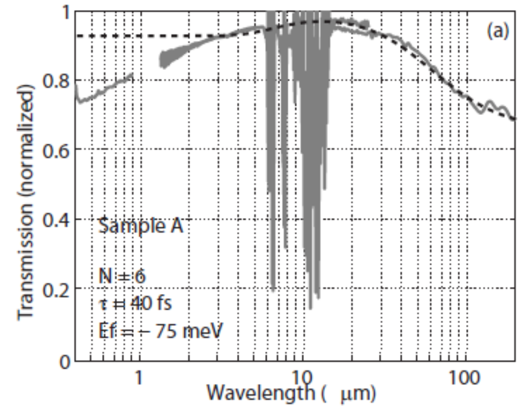
L. A. Falkovsky, Journal of Physics **129**, (2008).

Normalized Transmission with respect to Dirac Point Transmission



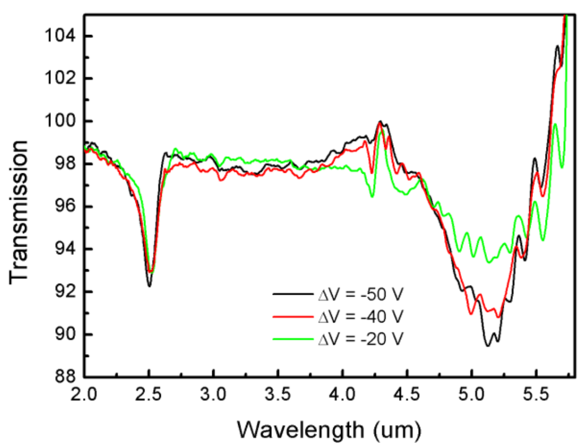
(T/ T_{Dirac})*100

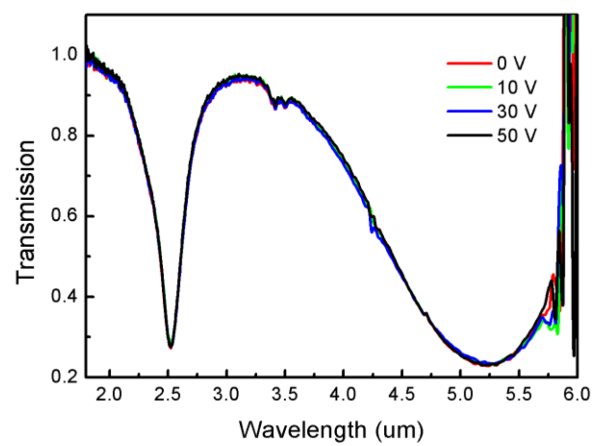
$\Delta V = V_{gate} - V_{Dirac}$



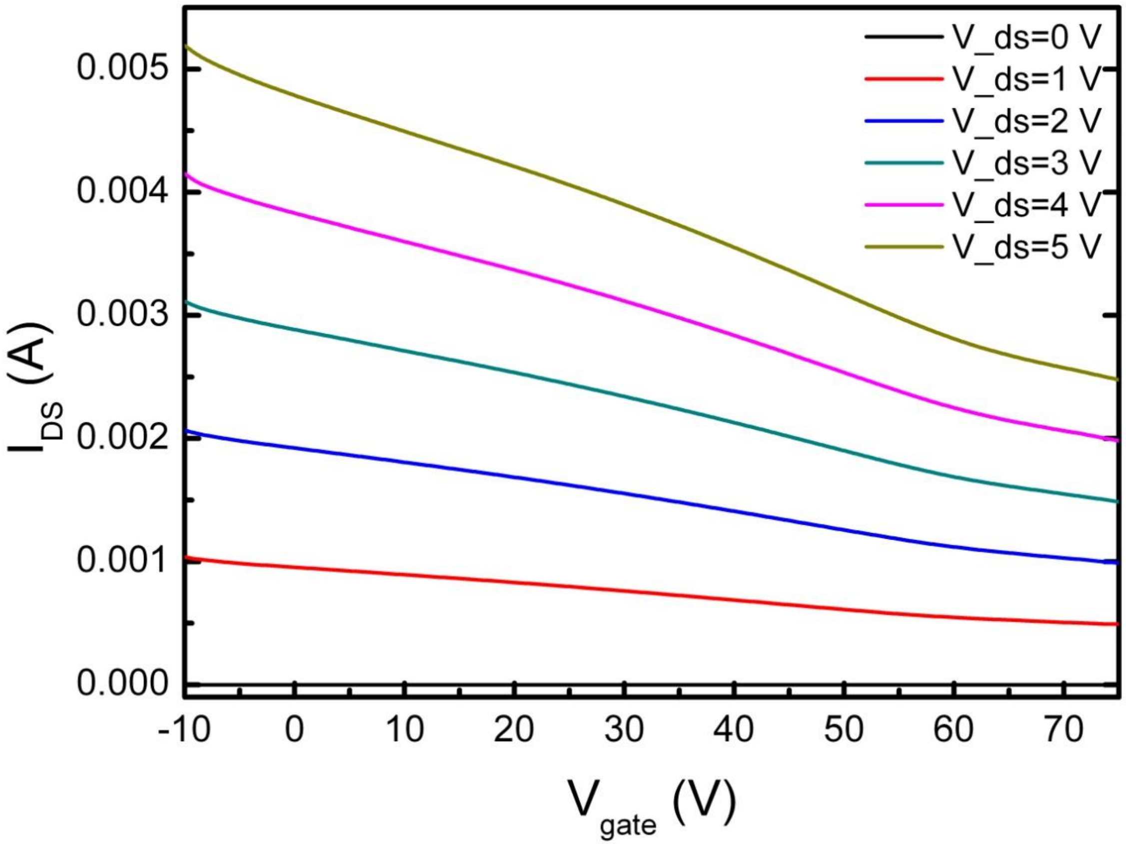
Multiphonon absorptions of SiC around 6-14 µm.

J. M. Dawlaty et al., APL **93**, (2008).

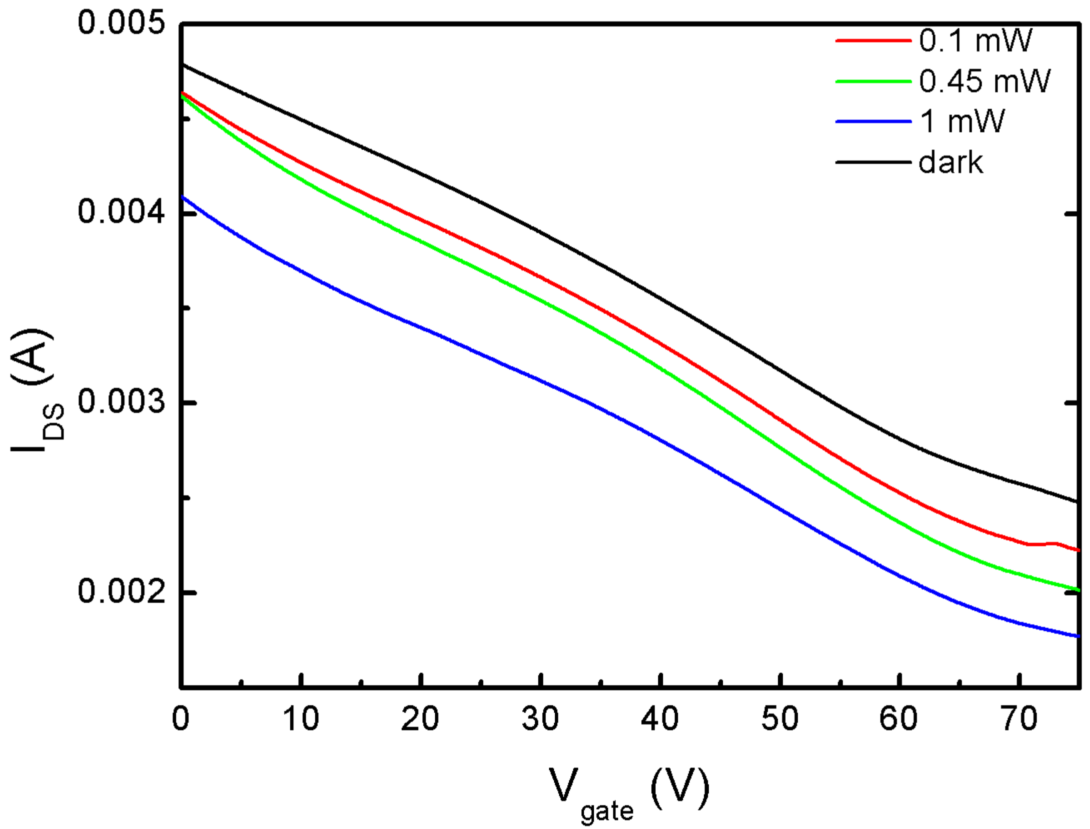




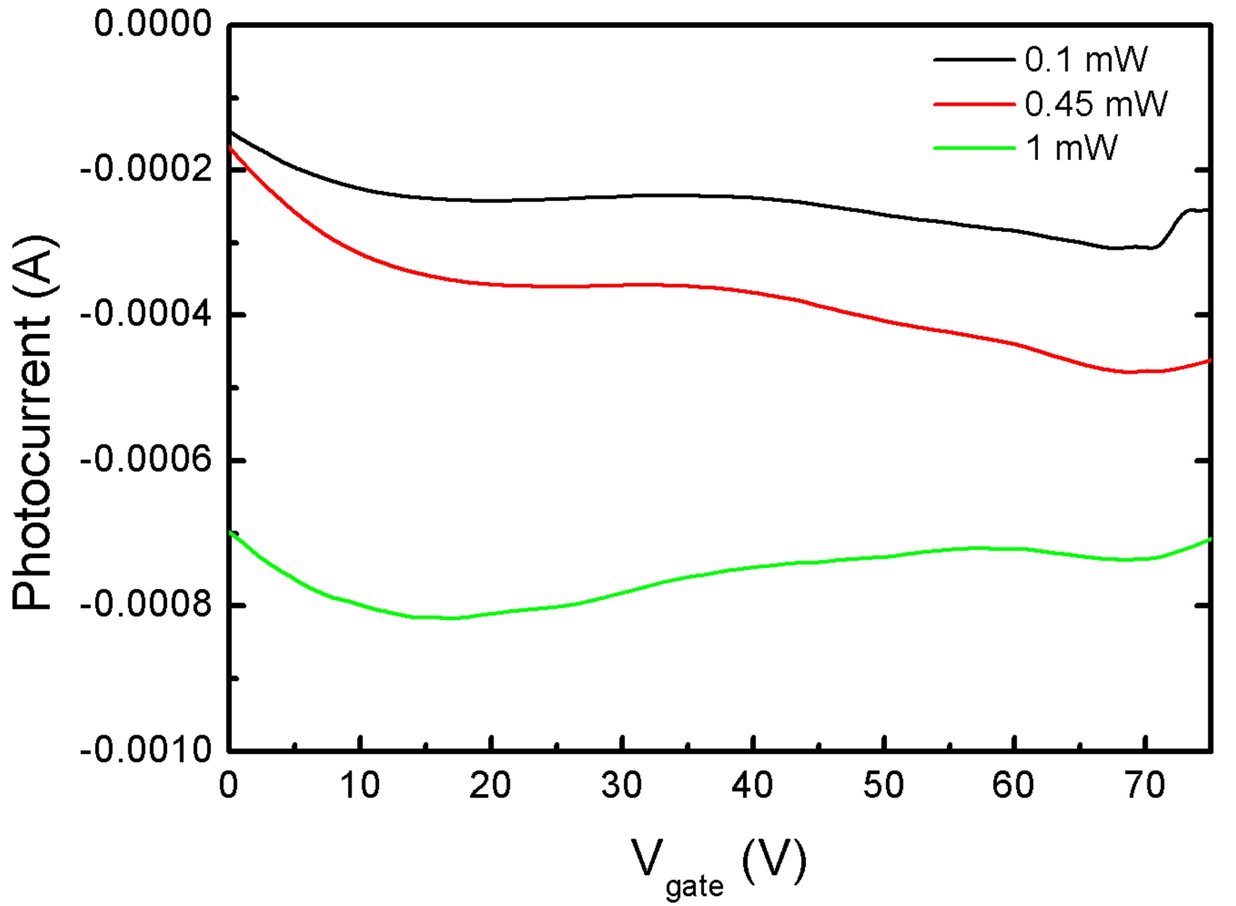
DC-IV Measurements of a Device with SRRs



DC-IV Measurements of a Device with SRRs

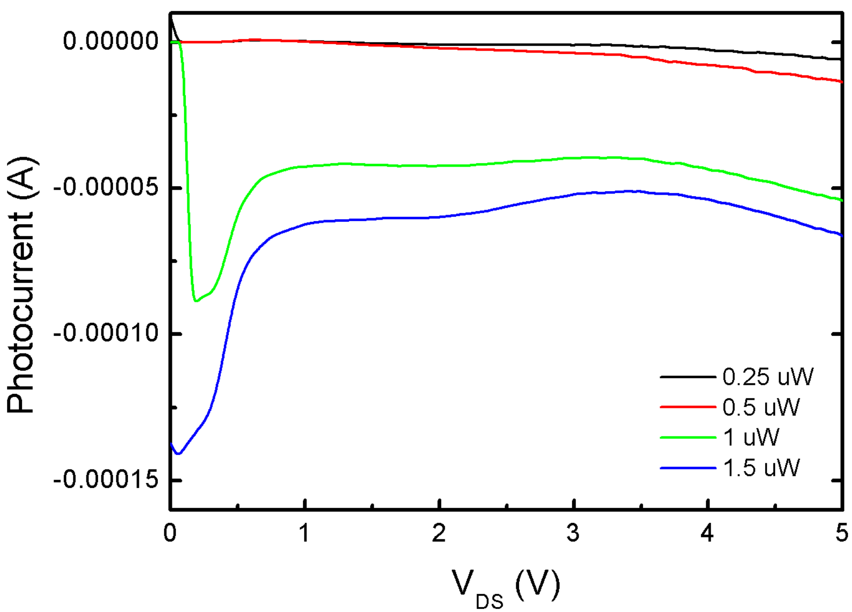


Photocurrent vs Gate Voltage

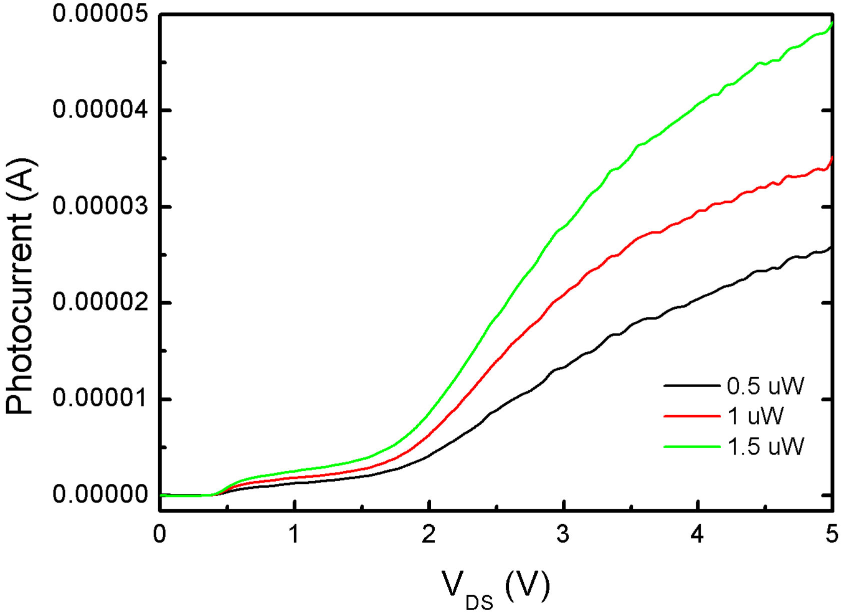


Photocurrent under different laser power at 10 V gate bias

Graphene with SRRs



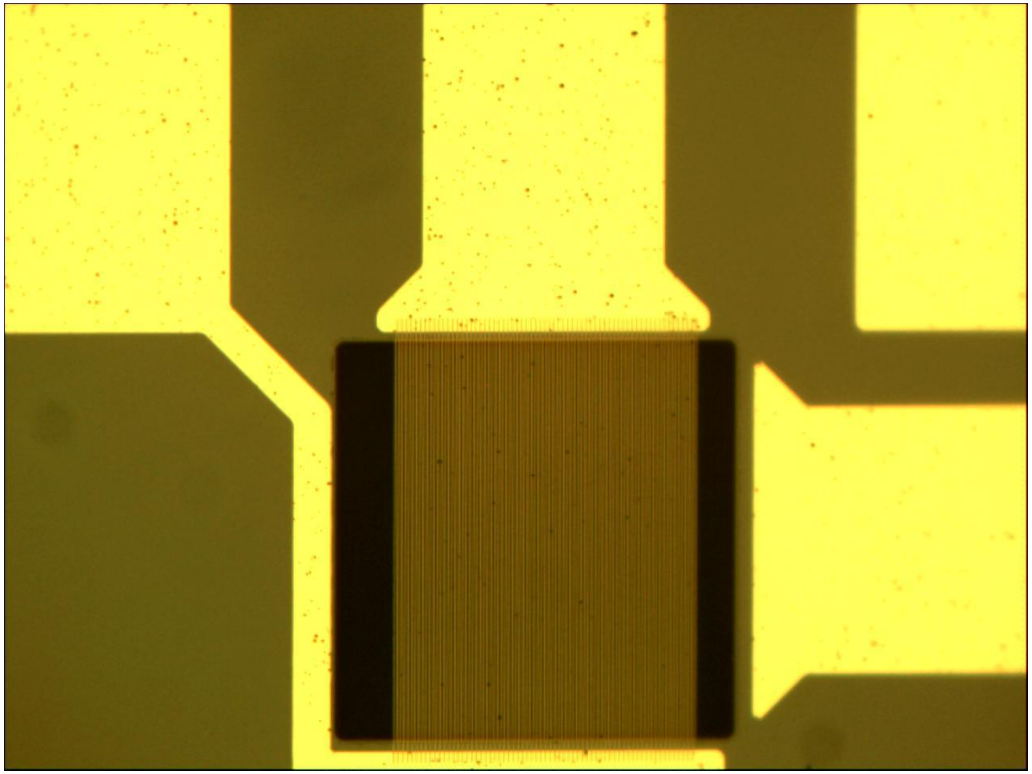
Bare Graphene

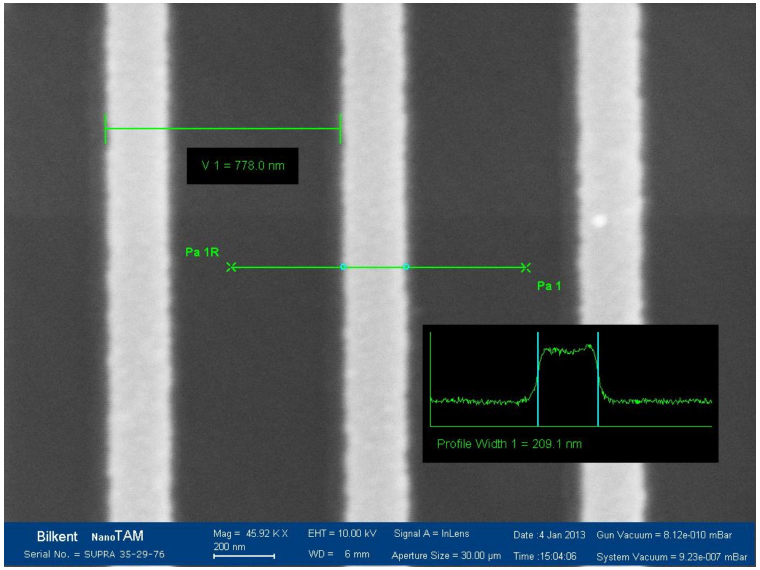


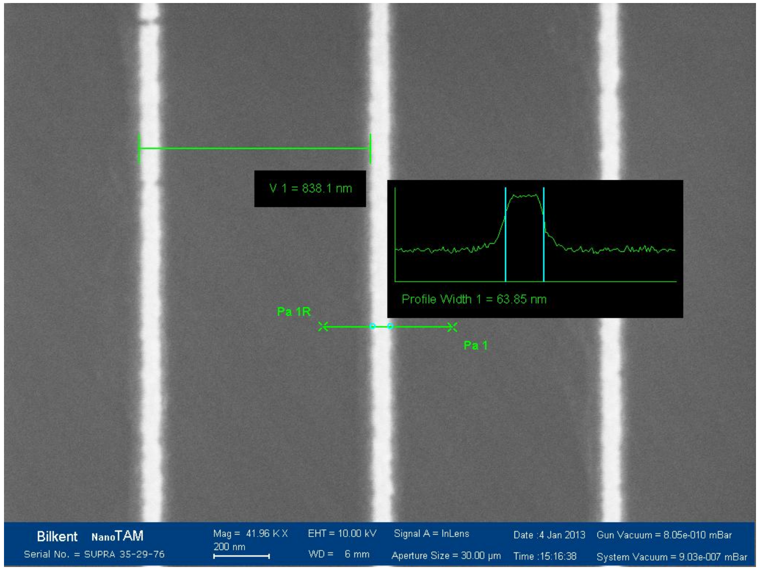
Bolometric effect: Electromagnetic wave is heating up the graphene. (?)

M. Freitag et al., Nature Photonics **7**, (2013)

Future Work: Metal-Graphene-Metal Photodetector







Conclusion

- Electrical properties of graphene was investigated
- Fabrication of gated plasmonic structures realized
- Broadening and damping of transmission were observed with varying gate bias
- This effect was studied with theoretical modeling and confirmed qualitatively.