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Carbon-based Electronics: Graphene

1st NANO-TEC Workshop
European Commission ICT Theme

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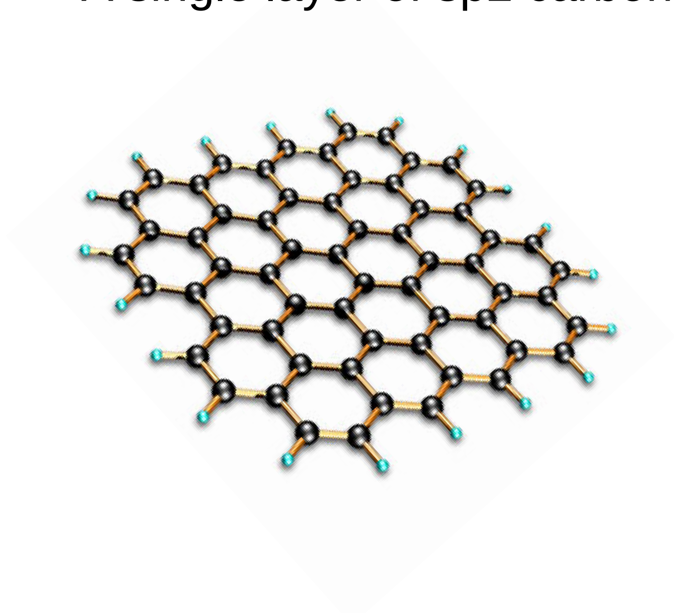
Content

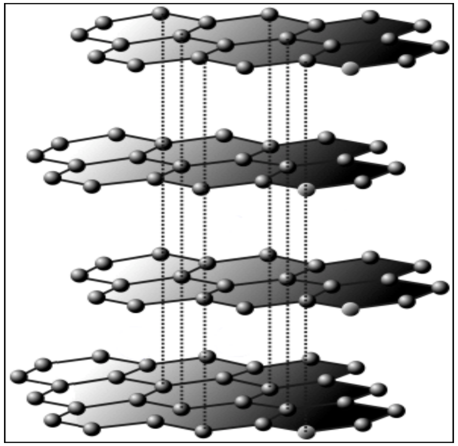
Graphene

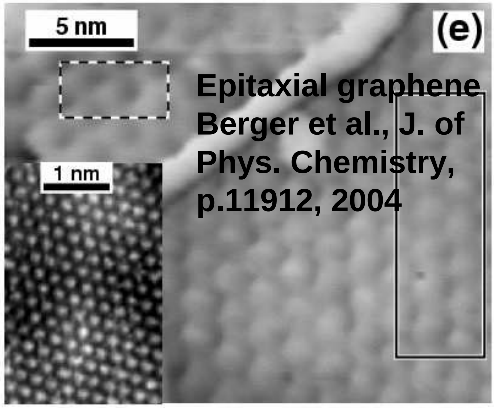
- Graphene = a single layer of carbon atoms in honeycomb lattice
- 2D structure instead of 1D nanowires or carbon nanowires
- Recent study of graphene was initiated by Prof. Geim's group and Prof. deHeer's group

A single layer of sp2 carbon



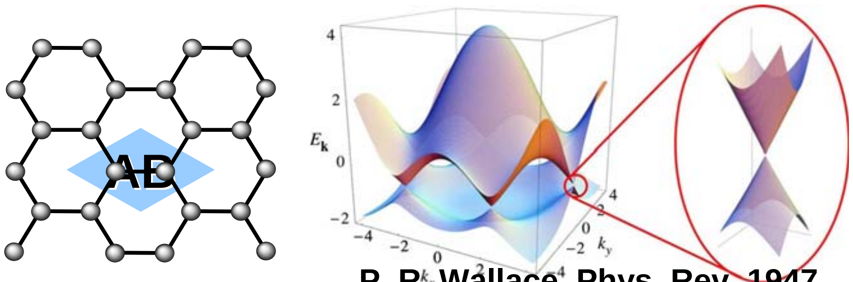
Graphite





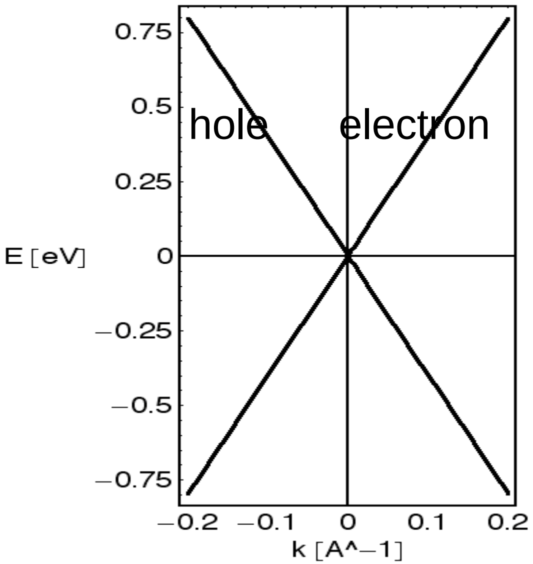
Graphene Band structure

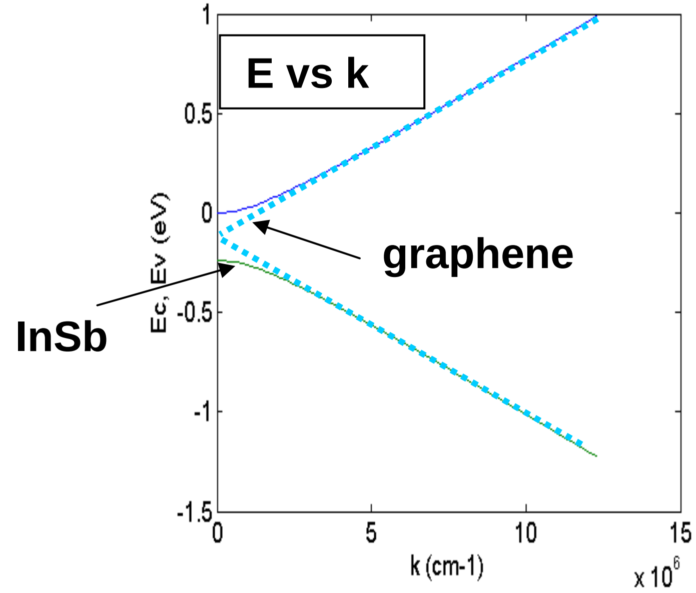
A single layer of graphene



Band structure:
- Zero bandgap
- Zero effective mass
- Linear dispersion

P. R. Wallace, Phys. Rev, 1947
A. H. Castro Neto, Rev. of Modern Physics, 2009





Zero bandgap → Ambipolar (n, p) characteristics

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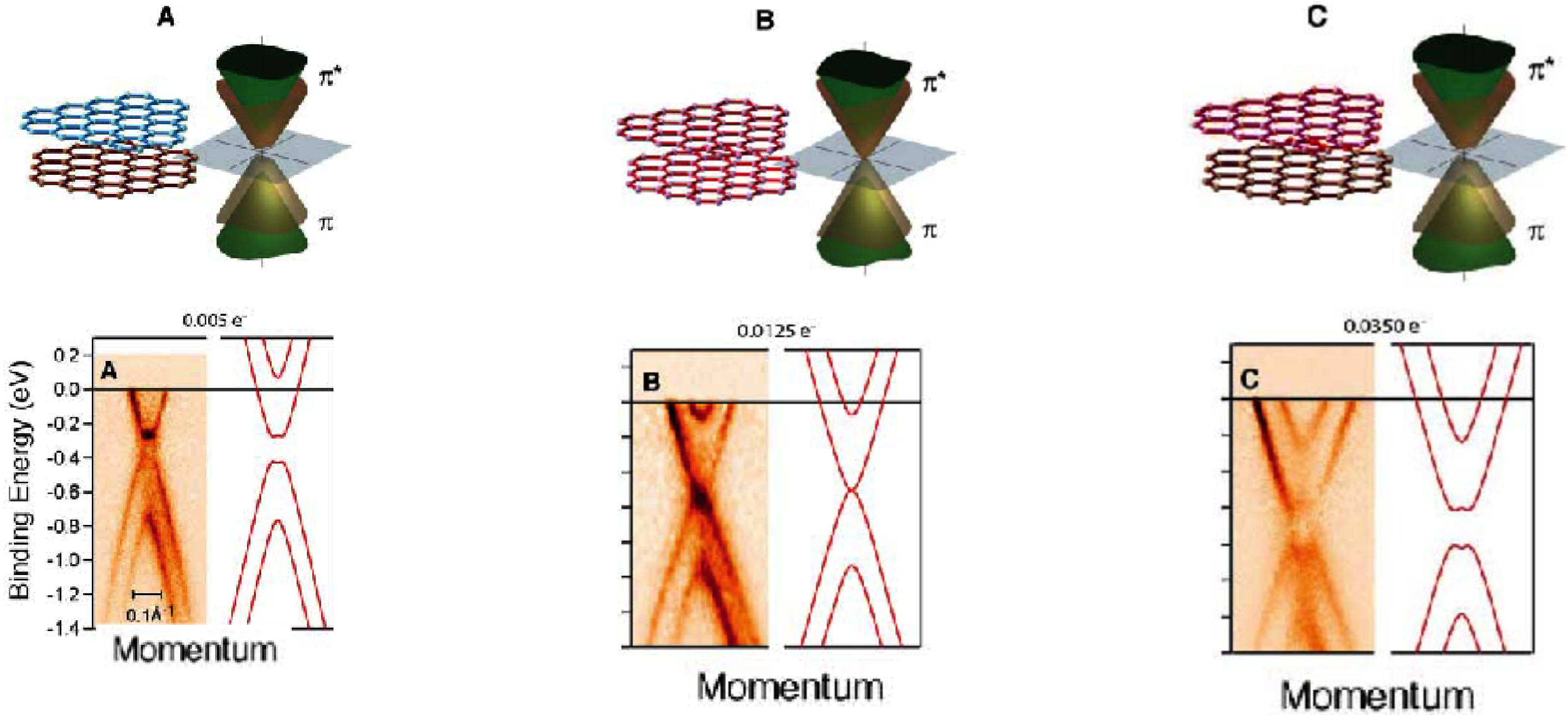
Bandgap Engineering

A bilayer graphene



Bottom layer more doped

Equally doped

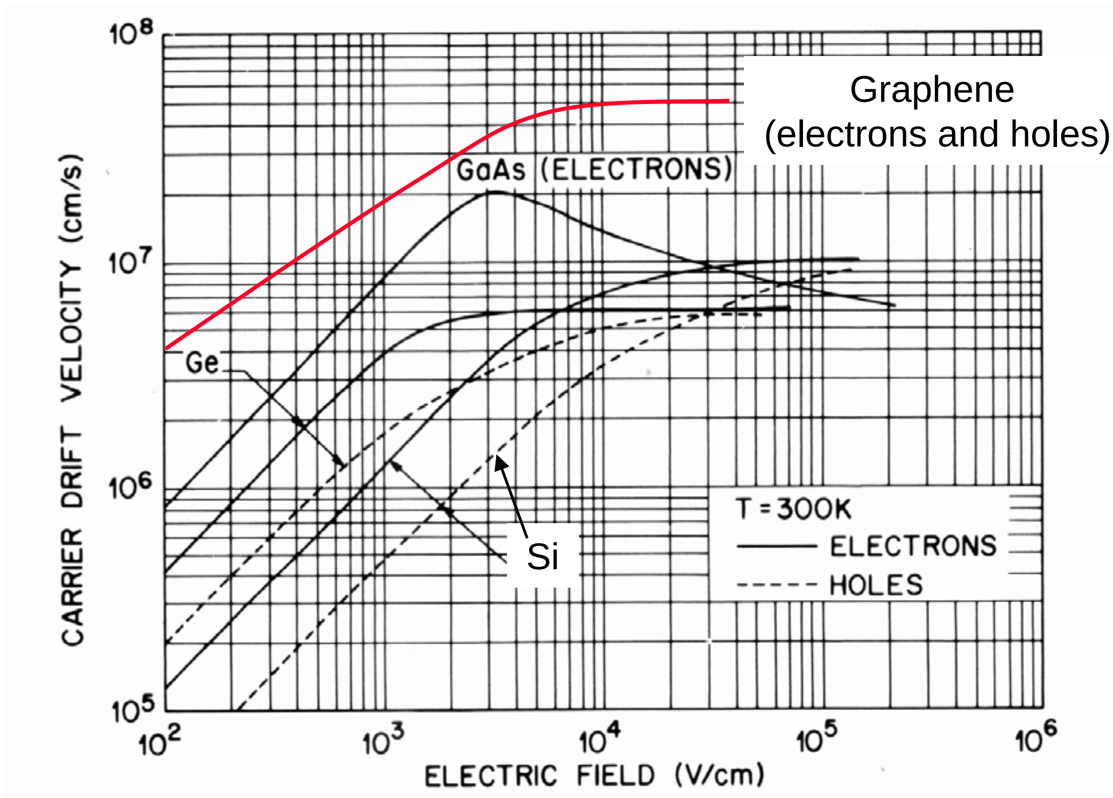
Top layer more doped

Ohta, Bostwick, Seyller, Horn and Rotenberg. Science 313, 951 (2006)

A bilayer graphene offers a bandgap of ~0.25 eV (~10 $k_B T_{room}$).

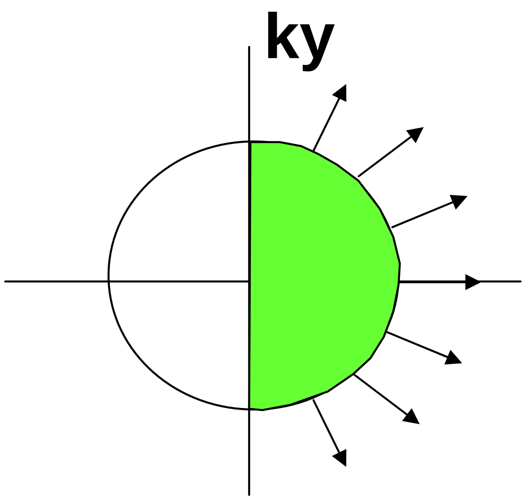
Graphene: Vsat and Critical field

Saturation Velocity (4.7x10^7 cm/sec)



Source Injection Velocity (6.4x10^7 cm/sec)

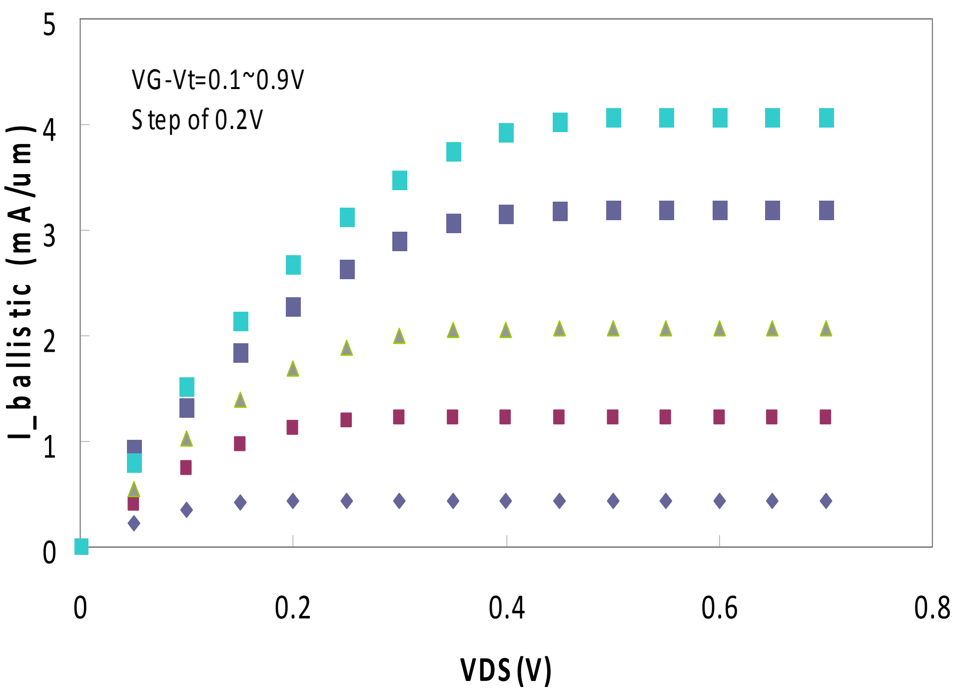
$<vx>=2/\pi\ V_F$



- Higher saturation velocity can be achieved at reduced electric field from graphene.
- Offer highly-scaled ballistic transistors.

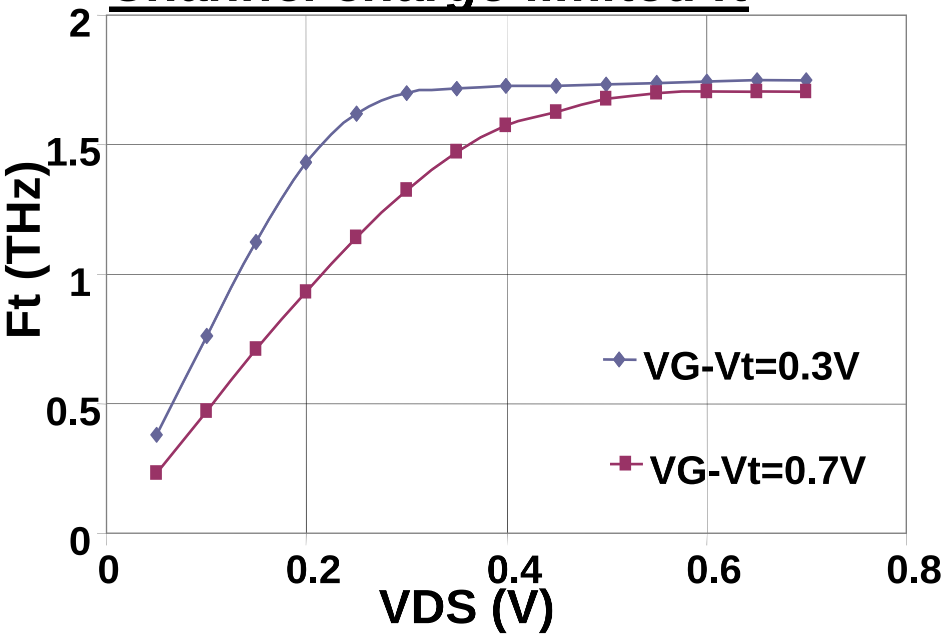
Ballistic Graphene FET Characteristics

2D model with full electrostatics
Initial calculation: ignores tunneling from valence band



Lg=60 nm
EOT=2 nm

Channel charge-limited ft



Effective transit time Ttr=1/2π ft

For ft=1.7 THz, Ttr=94 fsec
For Lg=60nm, veff~6e7 cm/sec

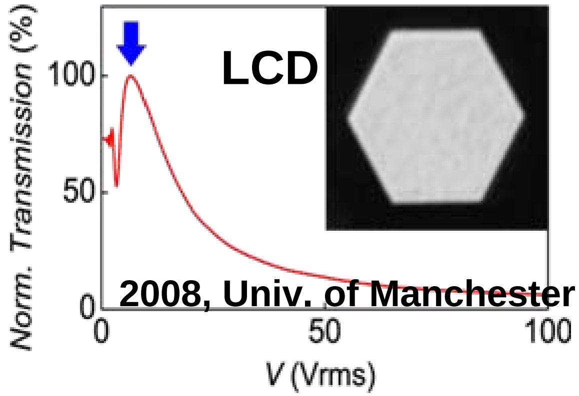
How does Graphene Compared with?

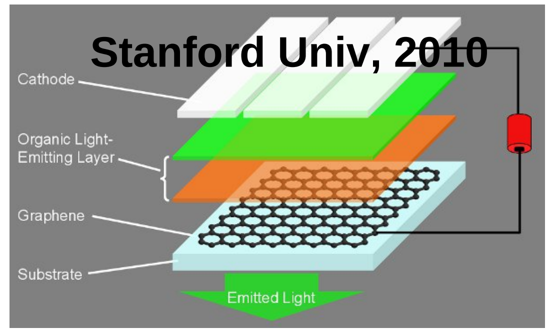
Merit	Si	Graphene	GaAs	$In_{0.53}Ga_{0.47}As$	InAs	InSb
Mobility (cm^2/vs)	1000 (n) 300 (p)	15000~ 200000	5000	11000	16000~ 26000	30000
Vsat (cm/sec)	8e6	~ 5e7	1.2e7	2.7e7	4e7	5e7
Bandgap (eV)	1.12	0~0.2max	1.43	0.72	0.36	0.18
Carrier density (cm2)		5e12 ~1e13		2~2.5 e12	1.3e12	1e12
MOS Scaling		High				
Si CMOS compatibility		High	Low	Low	Low	Low

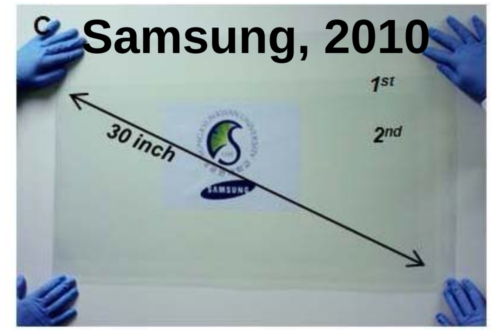
Properties of Graphene

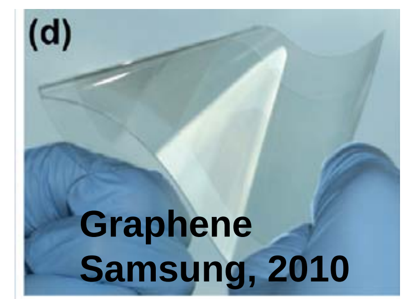
- Zero-band gap with bandgap engineering possibility
- Fermi Velocity = 10^8 cm/sec (10x better than Si)
- Saturation velocity = $5x10^7$ cm/sec (~2x faster than InP)
- Mobility (room temp) ~100000 cm^2/vs (~10x better than III-V)
- Current density = 10^9 A/cm^2
- Highest quality material on flexible substrates (~100-1000x better than any other flexible electronics materials known)
- Highest optical transparency
- Thermal conductivity ~48 W/(cm K) (~2x better than diamond)
- Young's modulus = 500 GPa (~better than SiC, 1.2 TPa diamond)
- Lowest mass and high surface-to-volume ratio
- Thermoelectric energy conversion
- A single molecule sensing

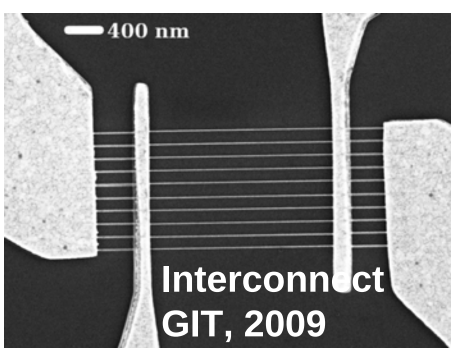
Potential Applications of Graphene

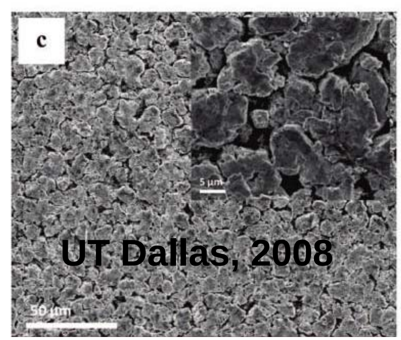


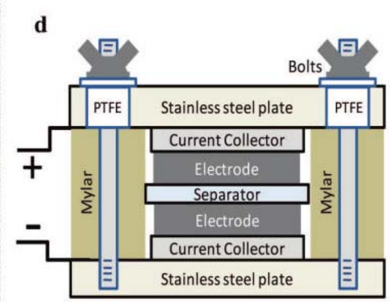






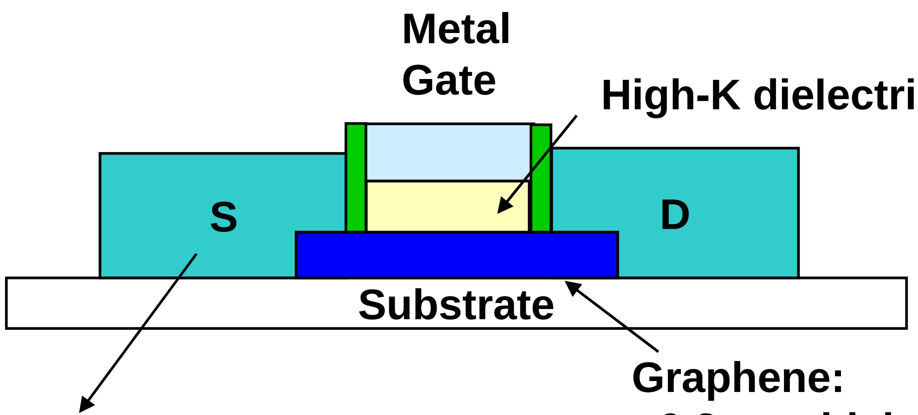






A Path for ultimate Scaling of MOSFET

- Self-aligned (n, p) MOSFET
- Advantage for device scaling



- Non-alloyed ohmic preferred
- Low ohmic contact Resistance

Graphene:
- 0.3 nm thick
- maintain high (n,p) mobility
- high channel velocity
- high phonon energy
- high thermal conductivity (lower Tj)
- High drive current

Graphene Transistor Development Phase

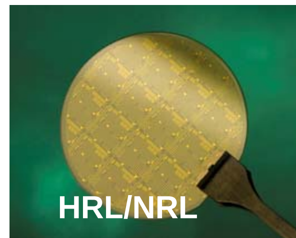
Rapid Growth of Graphene S&T:

Graphene-on-SiC
Graphene-on-Si

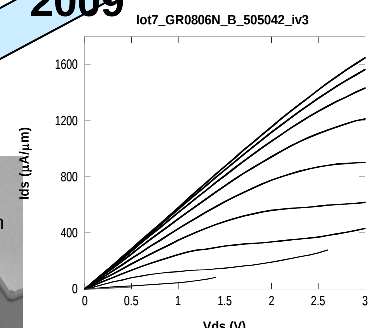
A world's first
3" graphene-on-Si

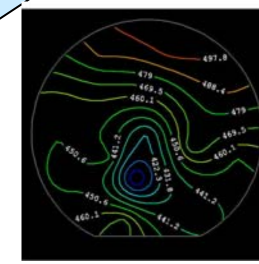
2010

A world's first
2" graphene MOSFET

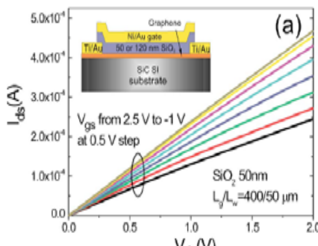


2009





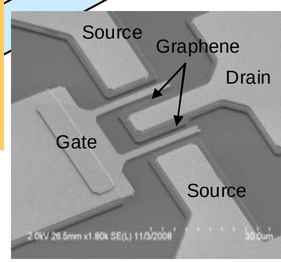
75mm graphene-on-SiC wafer (NRL/HRL)



Gm= 1.4 mS/mm

Wu et al., 2008

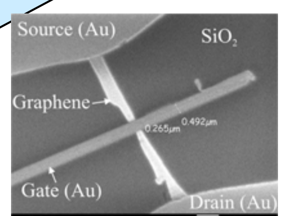
CERA June, 2008



Novoselov et al., Science, 2004

2008

2007

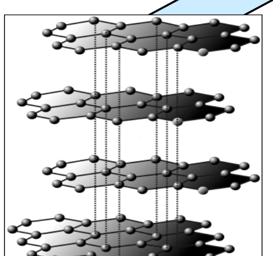


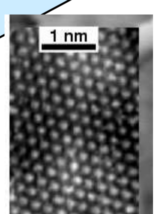
Lemme et al., EDL, 2007
Ion/Ioff < 3
FET mobility ~530 cm^2/Vs

A world's first Epitaxial graphene RF-FET (HRL, Dec, 2008)

Epitaxial graphene RF-FET
gm = 770 mS/mm,
Ion/Ioff = 33
FET mobility~ 6000 cm2/Vs
(HRL, 2009)

Graphite 2004



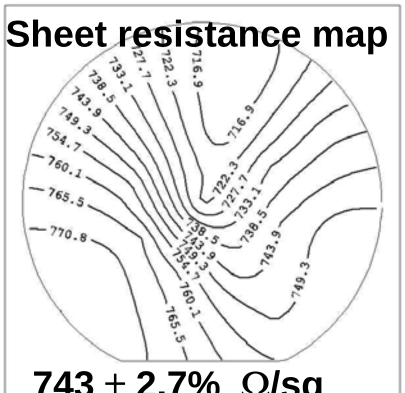


Epitaxial graphene
Berger et al., 2004

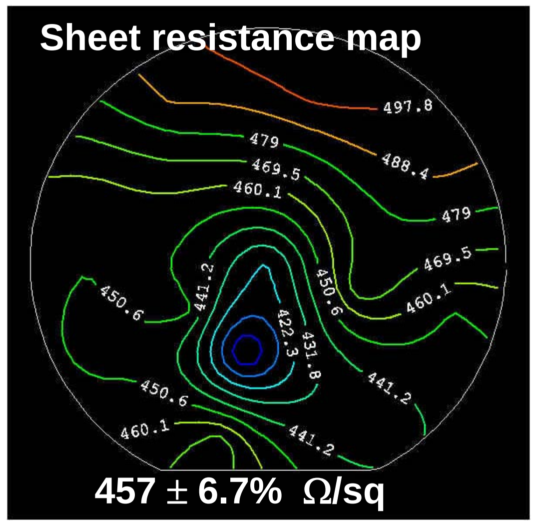
75mm Wafer-scale Graphene

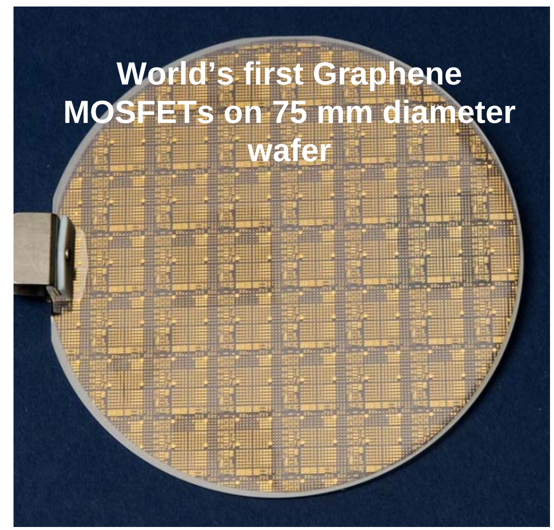
- **Epitaxial Graphene layers were grown on 50 and 75 mm diameter 6H-SiC wafers**

50 mm Epitaxial Graphene wafer



75 mm Epitaxial Graphene wafer

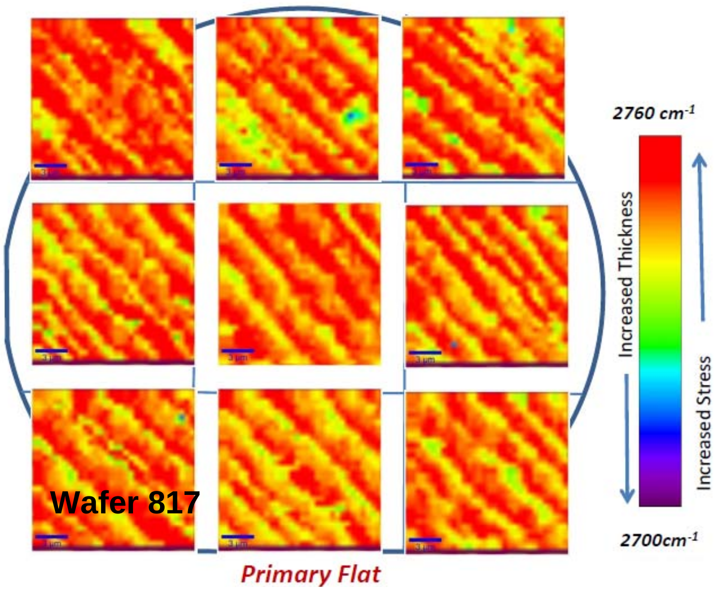




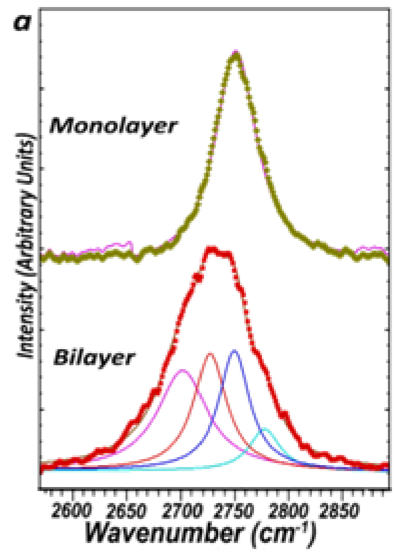
Graphene Layer

- Using spectral Raman, 22500 sites were analyzed.
- The nGL was determined by fitting the 2D spectra.
- The findings were correlated with transmission electron microscopy (TEM).

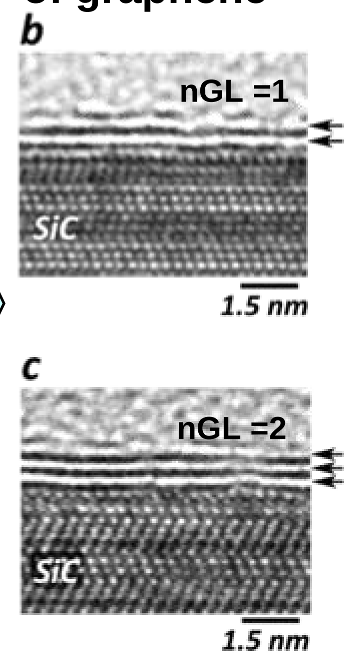
Map of 2D Raman spectrum position



Analysis of 2D Raman peaks



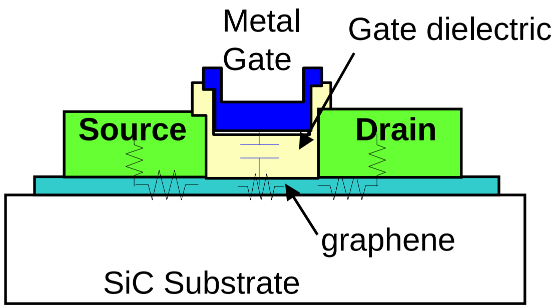
TEM Analysis of graphene

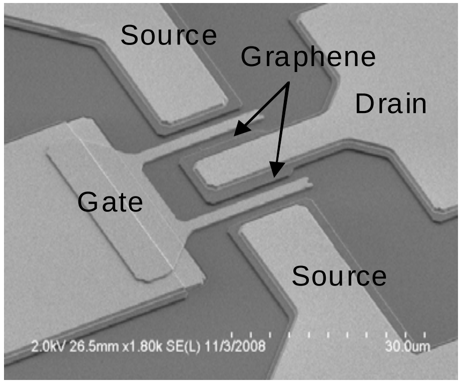


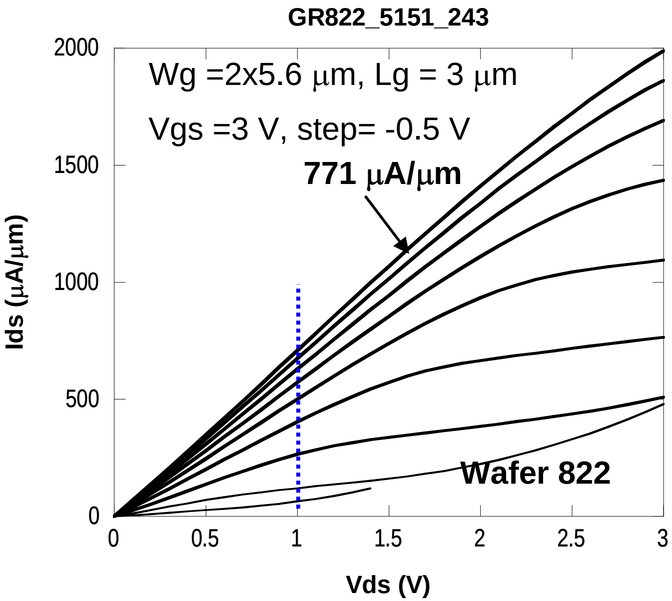
• Raman spectral analysis shows single and bilayer graphene on an entire 2” wafer.

Self-aligned Graphene MOSFETs

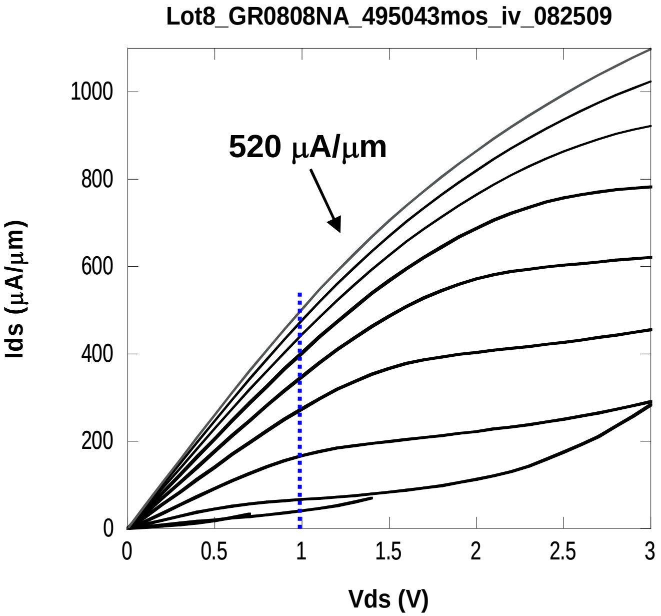
- Self-aligned MOSFET
- Gate dielectric and metal gate







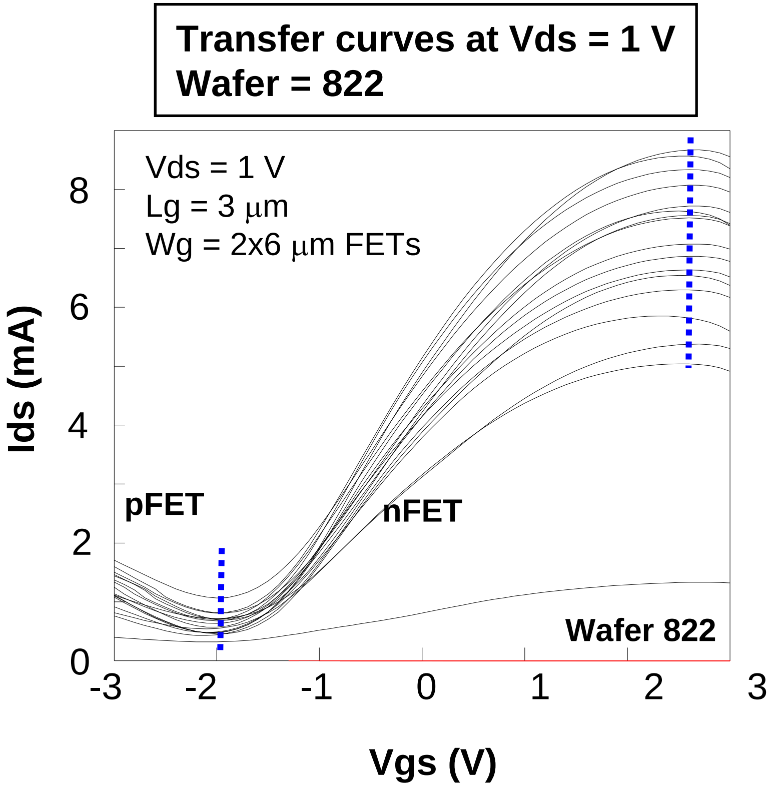
Vds = 1V:
Ion = 770 μA/μm



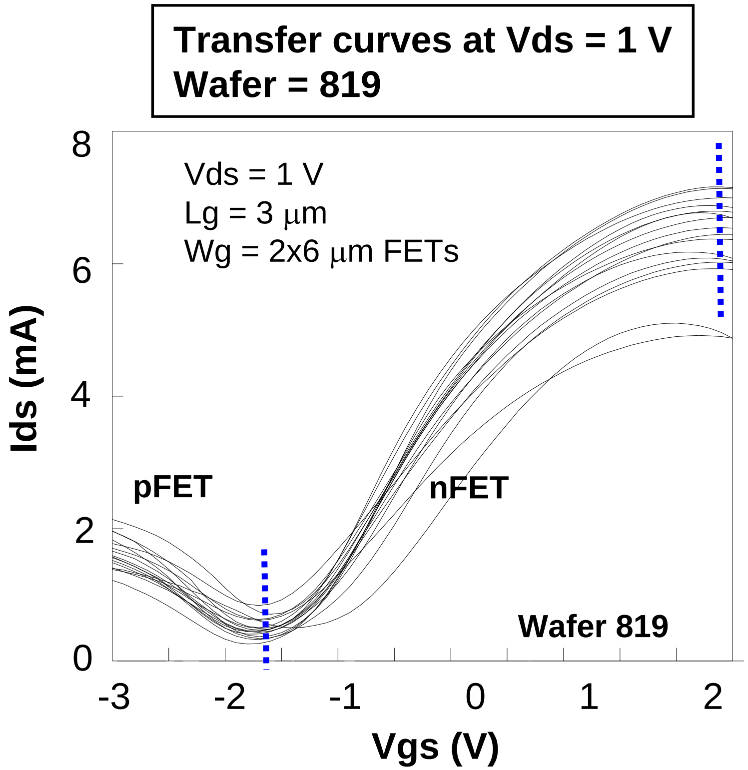
Vds = 1V:
Ion = 520 μA/μm

Ion/Ioff at Vds = 1 V

- **Graphene MOSFETs show an maximum Ion/Ioff of 26 at Vds = 1 V.**

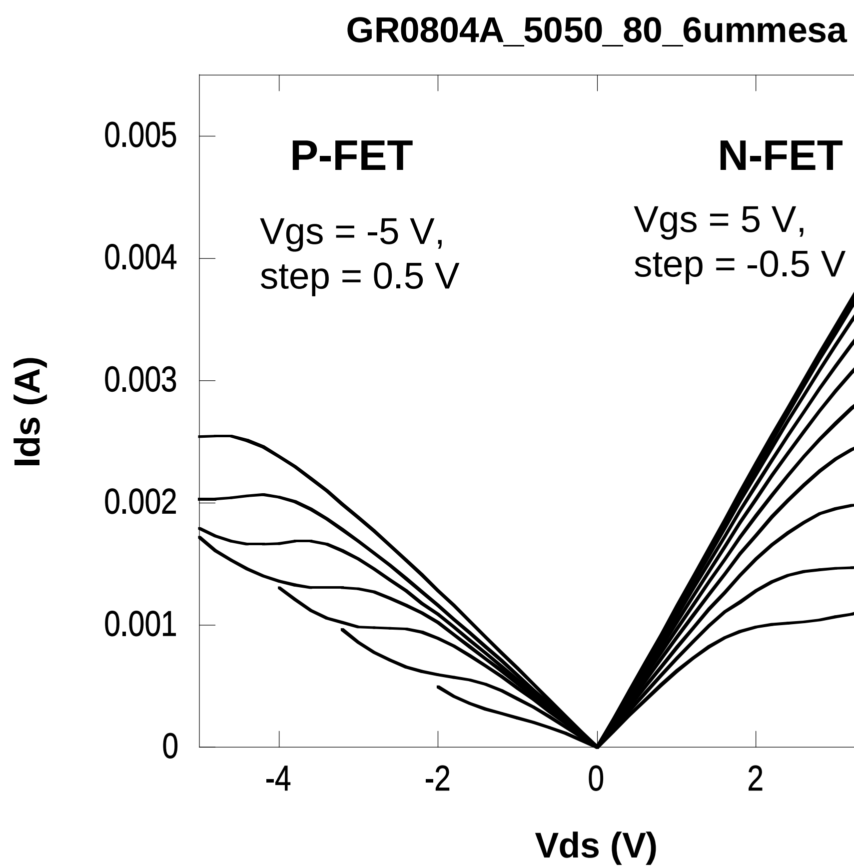


Vds = 1 V
Max. Ion/Ioff = 18



Vds = 1 V
Max. Ion/Ioff = 26

Graphene RF N-MOSFET & P-MOSFET



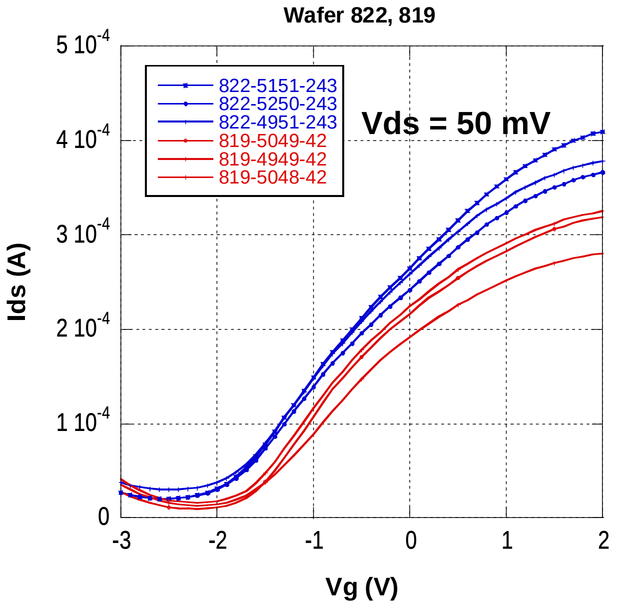
Graphene p-MOSFET and n-MOSFET are demonstrated

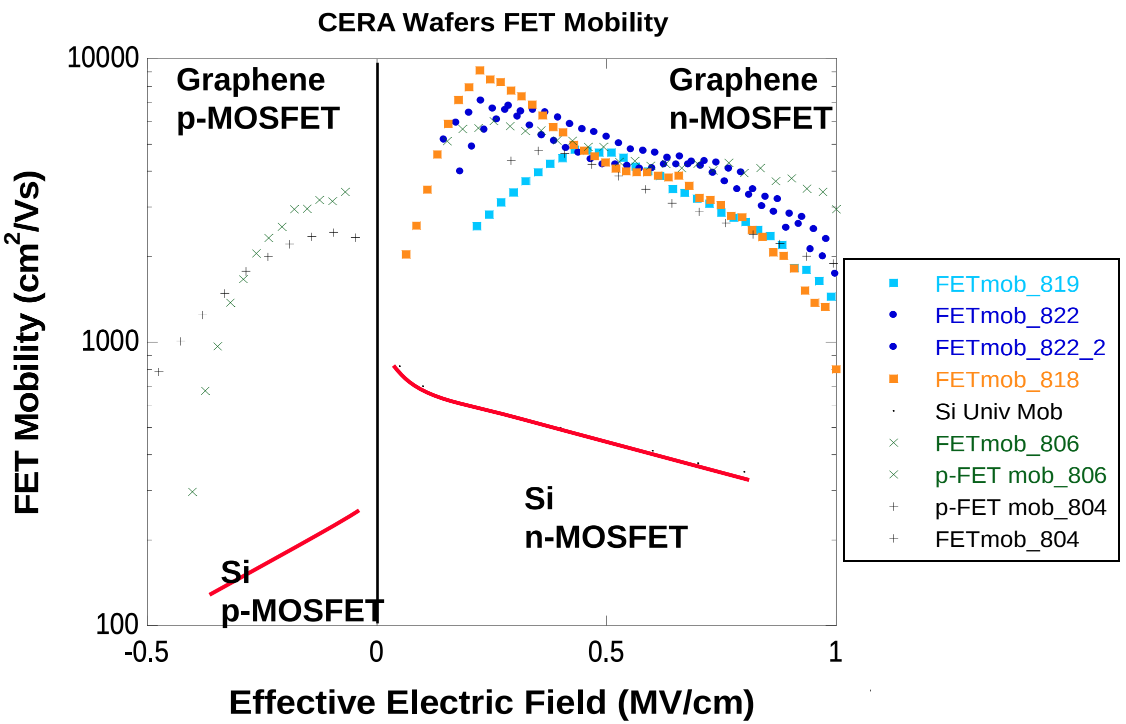
Graphene (n,p) MOSFET FET Mobility

Graphene MOSFETs show a record peak FET mobility of 9100 cm²/Vs.

$$\mu_{FET} = (L/W)\,(gm/C_g)\,(1/Vd).$$

MOSFET Transfer Curves



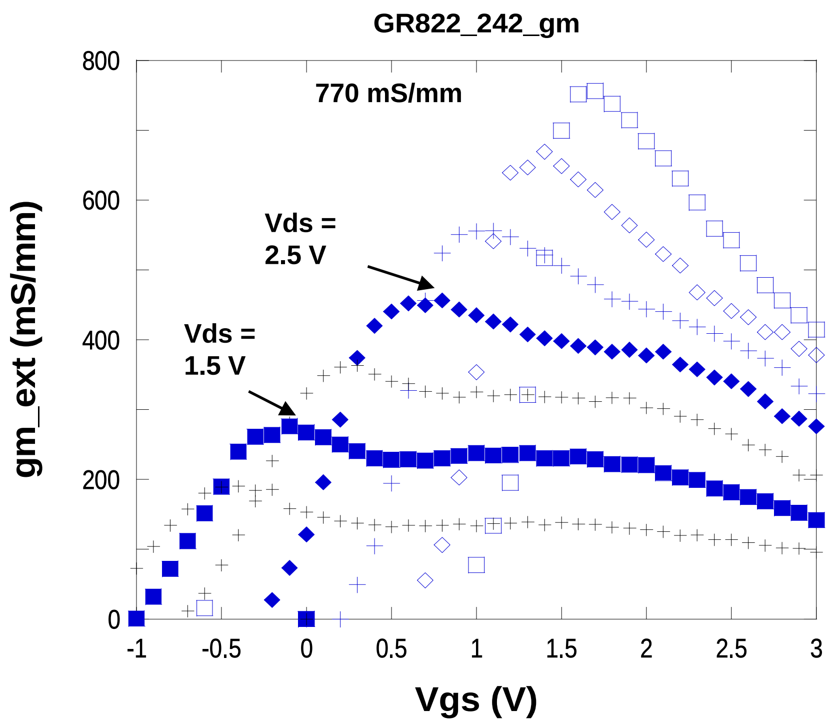


gm (50 mV) = 9-13 μS/μm

• Demonstrated 10X better FET mobility than that of Si CMOS

4. Carrier FET Mobility (≥5000 cm^2/Vs)

Long-channel (L_g = 3μm) Graphene MOSFETs show a record transconductance of 770 mS/mm at Vds = 4 V.

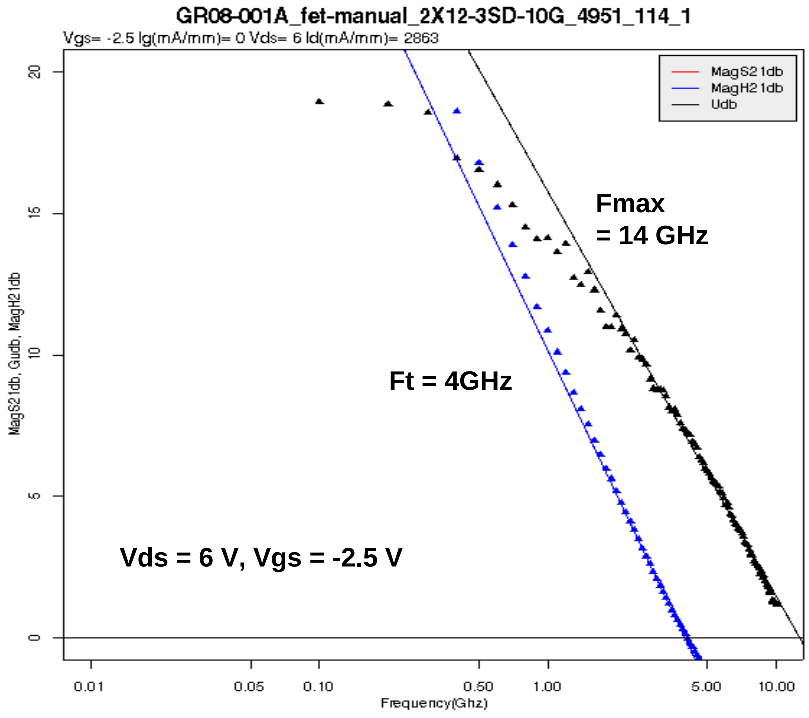


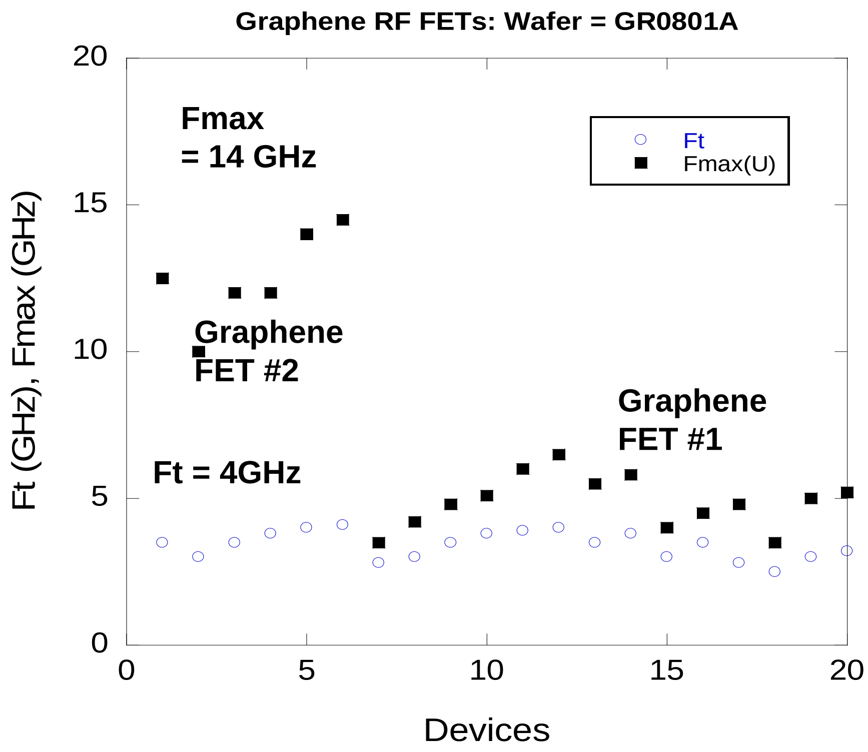
Long-channel graphene MOSFET:
L_g = 3μm
W_g = 2x6μm
Peak gm = 770 mS/mm at Vds = 4 V

A long-channel graphene MOSFET with a record gm/Cgs was demonstrated.

Graphene-on-SiC MOSFETs (2008)

- **Demonstrated wafer-scale graphene RF transistors operating in GHz domain.**

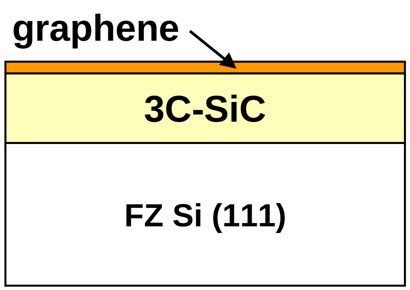


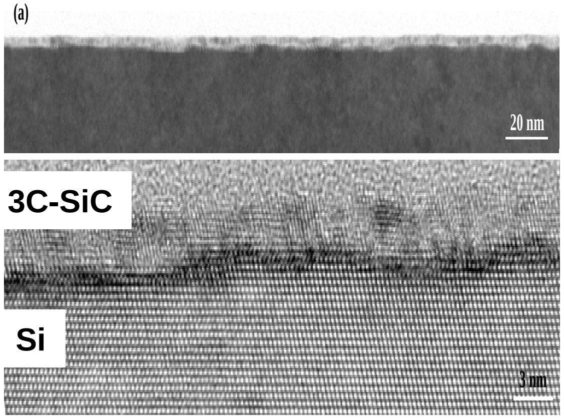


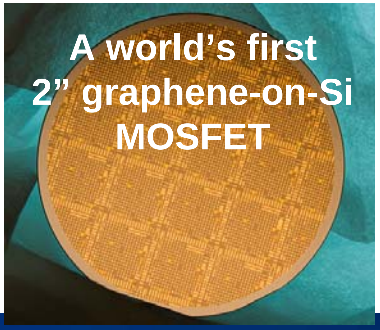
Graphene-on-Si Technology Development

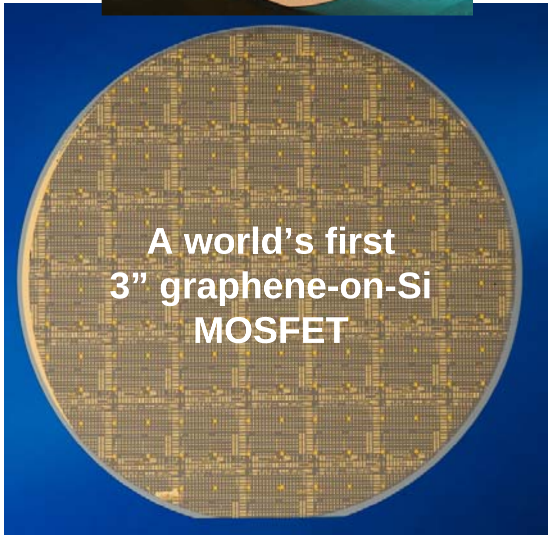
Graphene-on-Si technology offer a path toward very large-scale of graphene synthesis

Graphene-on-Si



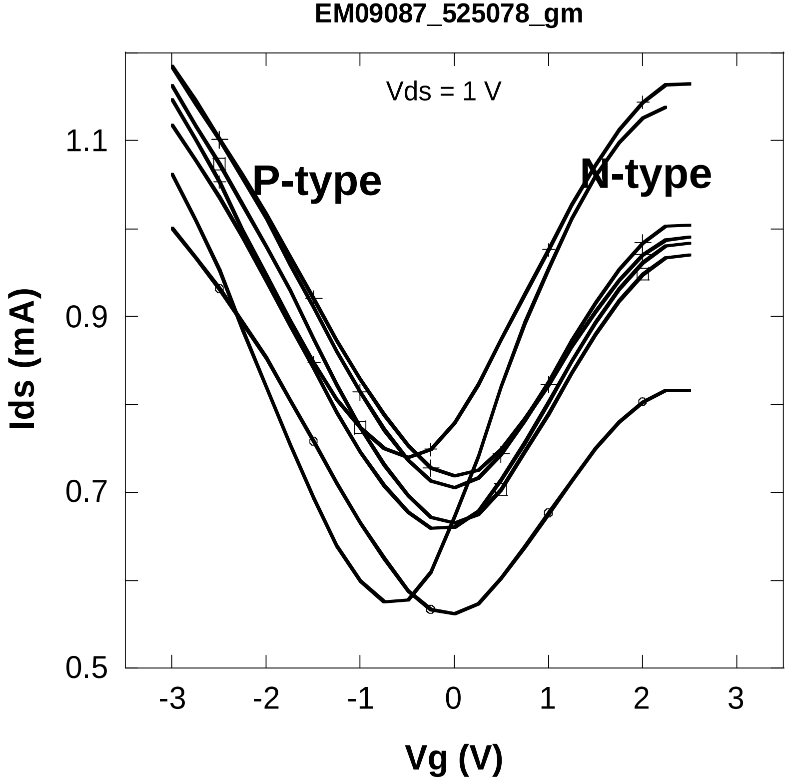


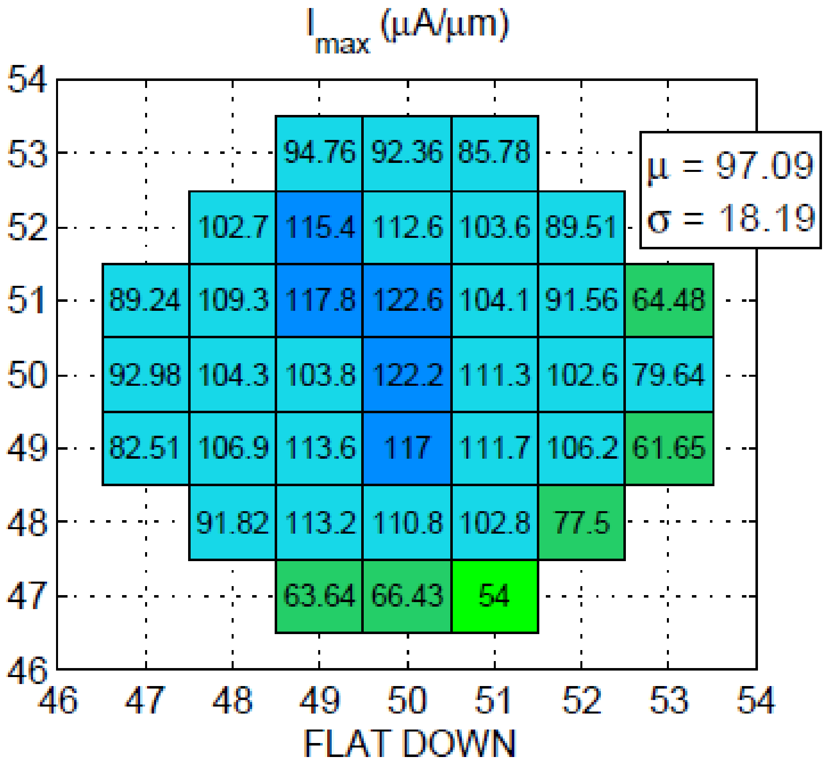




HRL/EOC, 2009

Ambipolar Graphene-on-Si MOSFETs





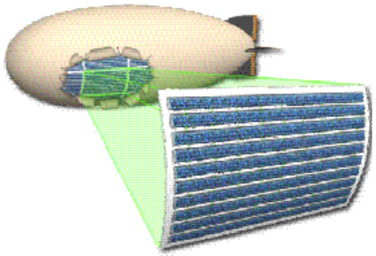
First demonstration of ambipolar (e & h) behaviors from graphene-on-Si

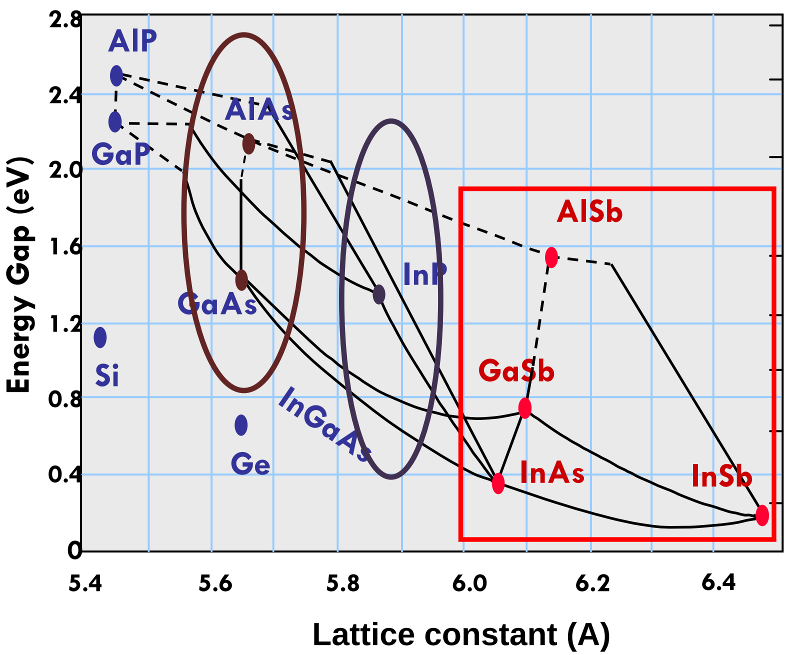
Semiconductor Comparison for Receiver

	Graphene MOSFET	Si MOSFET	GaAs PHEMT	InAs
2DEG($1/cm^2$)	1-10e12		2e12	1.3e12
Idss (A/mm)	0.8 – 3	1	0.5	
Hall Mobility (cm^2/vs)	>20000	1500	5000	26300
Vsat (cm/sec)	4.9e7*	8e6	2e7	3.5e7
Gm (mS/mm)	760		500	2000
K(W/cm-K)	48	1.5	0.54	0.67 (InP)
Ft, fmax	300, 300 (goal)	350,	120, 223	212, 270
LNA MMICs		86-108 GHz	77 GHz	94 GHz
Receiver-on-chip w/ integration density	Graphene-on-Si approach	SiGe 77GHz Radar	Need baseband processing	Need baseband processing

*** Based on gm/Cg**

Technology Needs for Ultra-Low-power & Linear Receiver





LNA Technology	Vds (V)	DC power/stage
0.18 um CMOS	1-2	~9 mW
0.13 um CMOS	0.8-2	~2-10 mW
InP	1.5	~11-15 mW
MHEMT	1.4	~5 mW
AlSb/InAs	0.15 -0.4	0.9 – 2.5 mW
Graphene	0-0.2	tbd

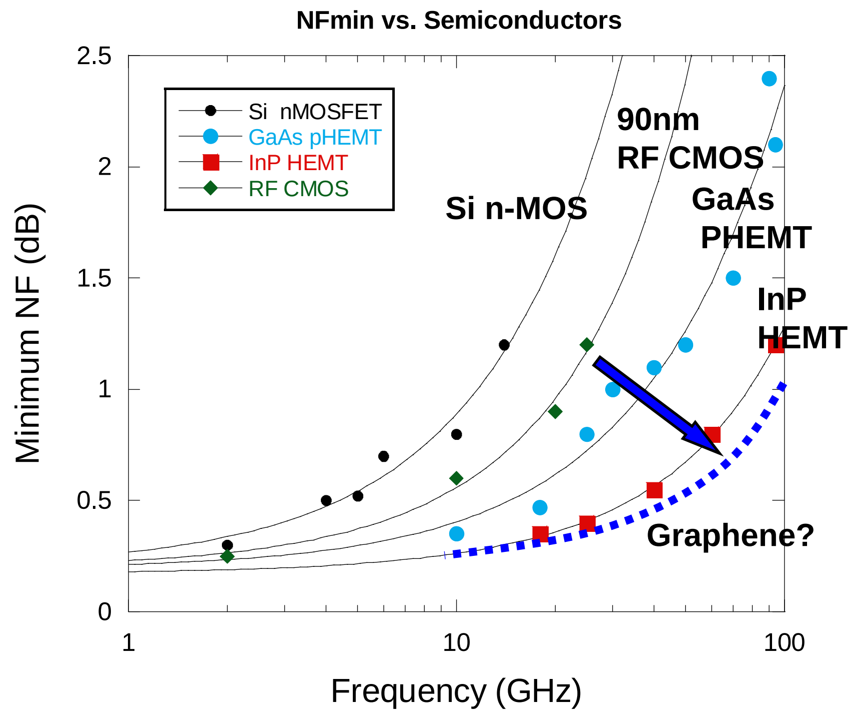
Lower bandgap devices offer low-power LNA operation.

Device F_{min}, Bandwidth, vs. Saturation Velocity

$$F_{min} = 1 + k \cdot f \cdot C_g \cdot [(R_s + R_g)/gm]^{1/2}, \quad f_T \sim gm/C_g \sim V_{sat}/(2\pi \cdot L_g),$$

$$\text{bandwidth: Rn (noise resistance)} \sim [1+(2\pi f^* Cg^* Rg)^2]/gm^2$$

Technology	Vsat (cm/s)	Bandgap (eV)
Si	8×10^6	1.12
GaAs	2.2×10^7	1.43
$In_{0.53}Ga_{0.47}As/InAlAs/InP$	2.7×10^7	0.72
InSb	$\sim5\times10^7$	0.18
Graphene	$\sim5\times10^7$	0-0.2



- High-performance LNA requires high Vsat.
- Graphene and ABCS HEMT offer the highest Vsat.
- Reduced Rn → wider bandwidth
- Provide low-noise performance over wider bandwidth

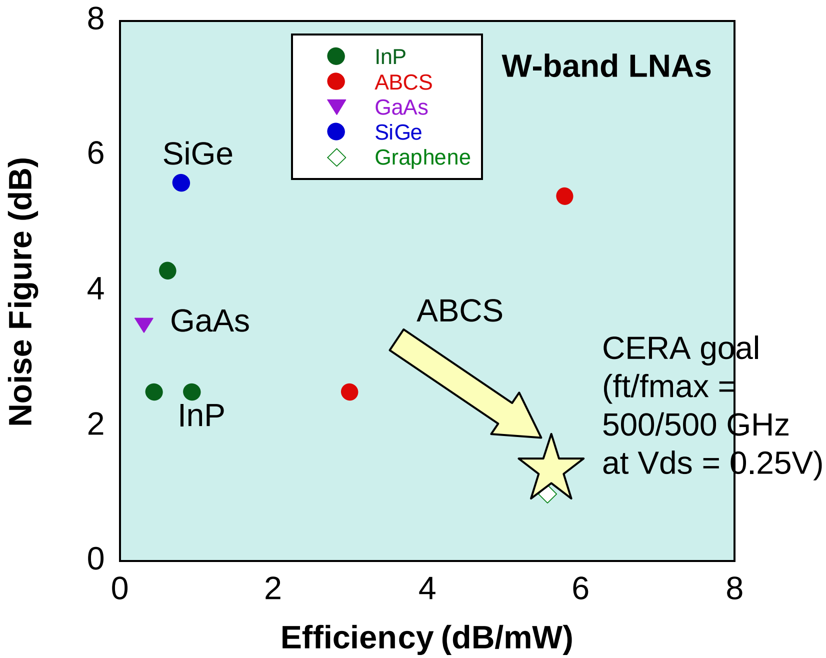
CERA and Linear LNA Figure of Merit

LNA FOM = gain*BW/[(NF-1)*P_{dc}]

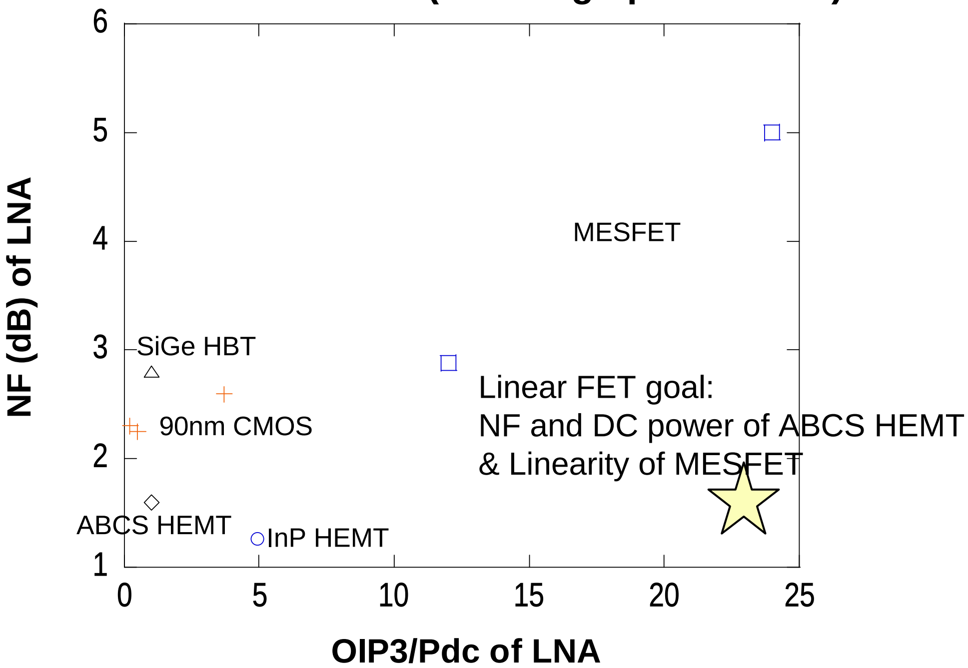
Linearity FOM = OIP3/P_{dc}

$$OIP3 \approx \frac{gm^3}{gm''} \times G_p$$

CERA program is designed to demonstrate W-band LNA



Wideband LNA (covering up to 10 GHz)



Question: Would graphene be high-performance linear FET?

Nonlinear RF: Clean & Efficient Signal Generation

Phase/Amplitude modulation in Digital Radio, Comm & spread spectrum:
Requirement of phase noise (QPSK)= -90 dBc/Hz at 100 kHz

Device: Ft, fmax, 1/f noise
Multiplier (xN): 10LogN

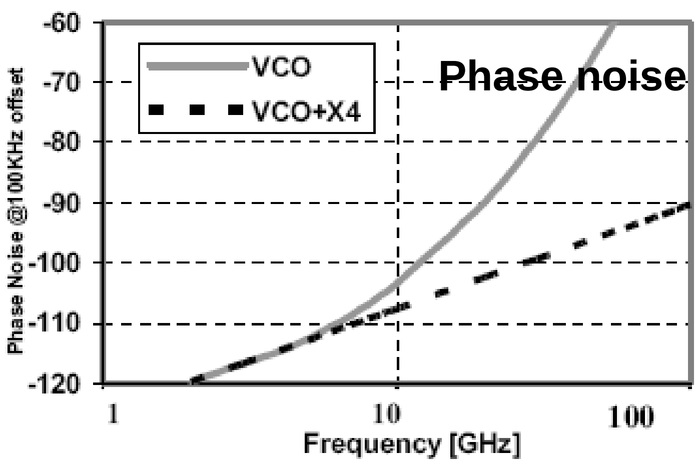
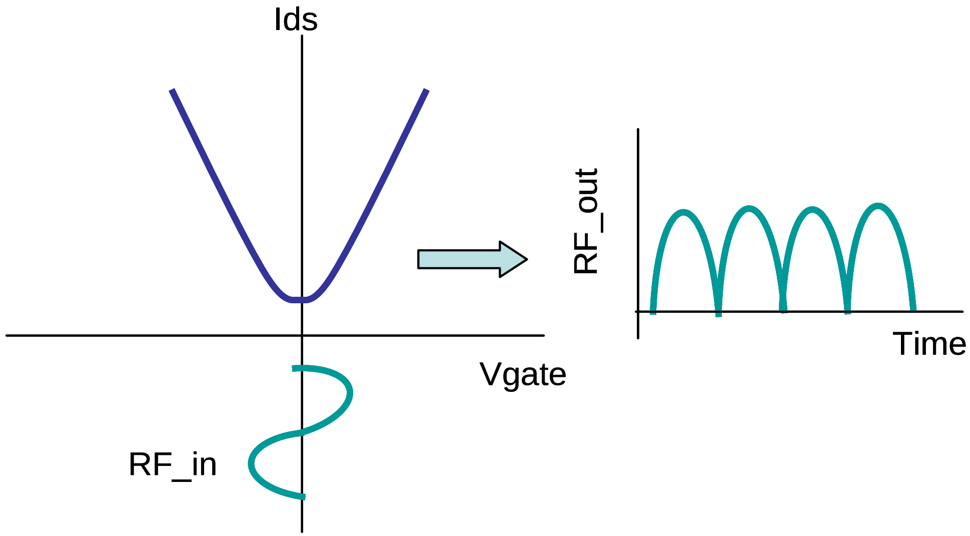


Fig. (1): Comparison of Phase Noise of a fundamental VCO and a low frequency VCO combined with X4 Multiplier

Edmar Camargo, Artech House, 1998

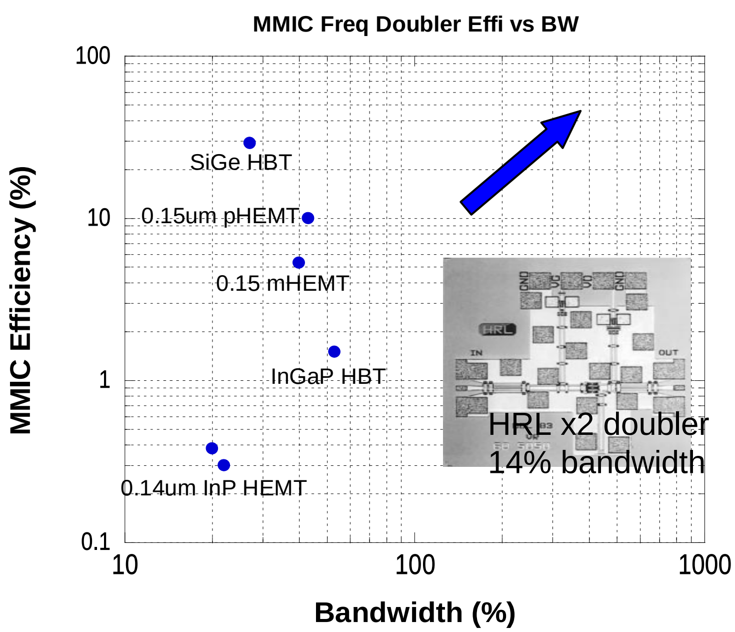
Frequency multipliers

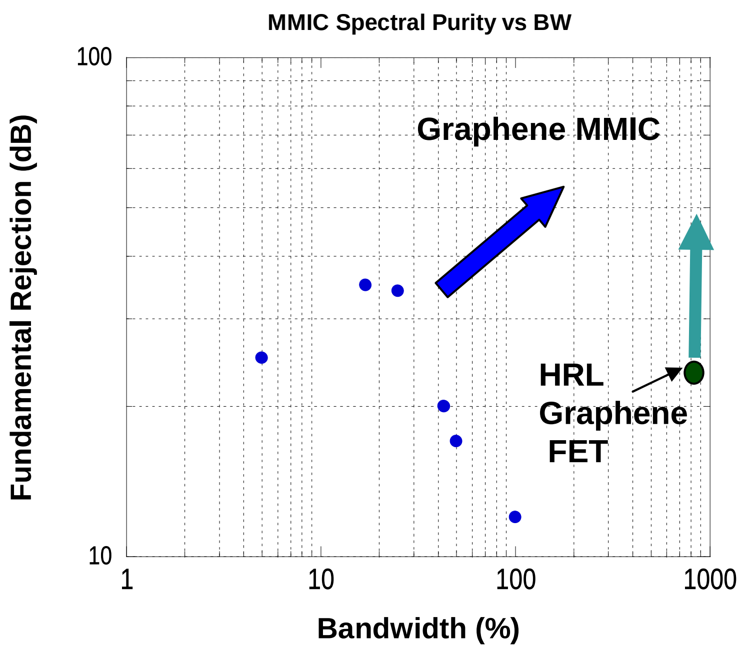


- **Spectral control**
- **Ft, fmax,**
- **1/f noise**
- **Phase noise**
- **Conversion efficiency**
- **Bandwidth**

Ultra wideband Spectrally-pure RF Signal Generation

RF systems need spectrally-pure ultra-wide band RF/MW/mmW signal generation. Until now, there are no clear technical implementation approaches.



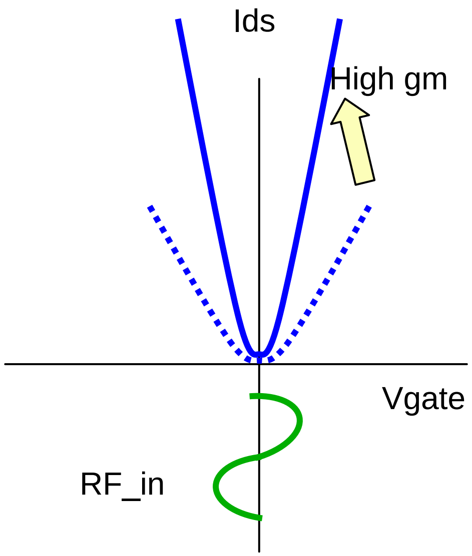


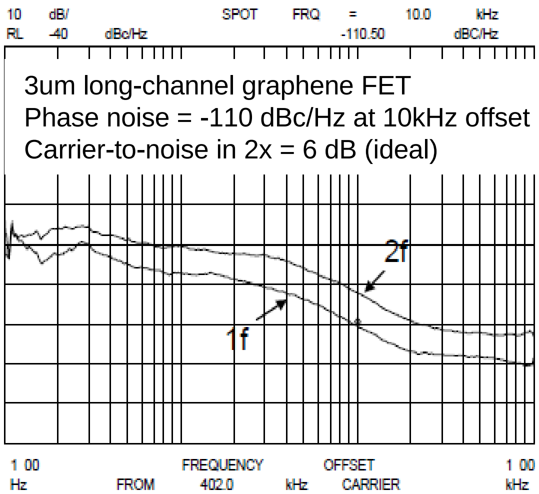
Graphene shows a feasibility and path for the desired signal generation.

Graphene for high-efficient & linear Mixer

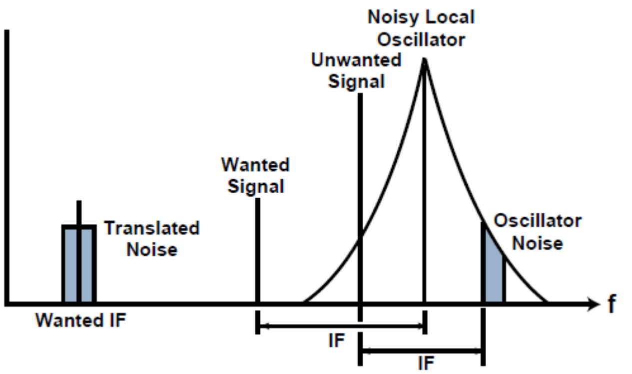
I ≈ β(gm) V2 (square-law device)

Mixer efficiency: $E_{sys} = \dfrac{IP_3(dBm) - LO(dBm)}{10}$



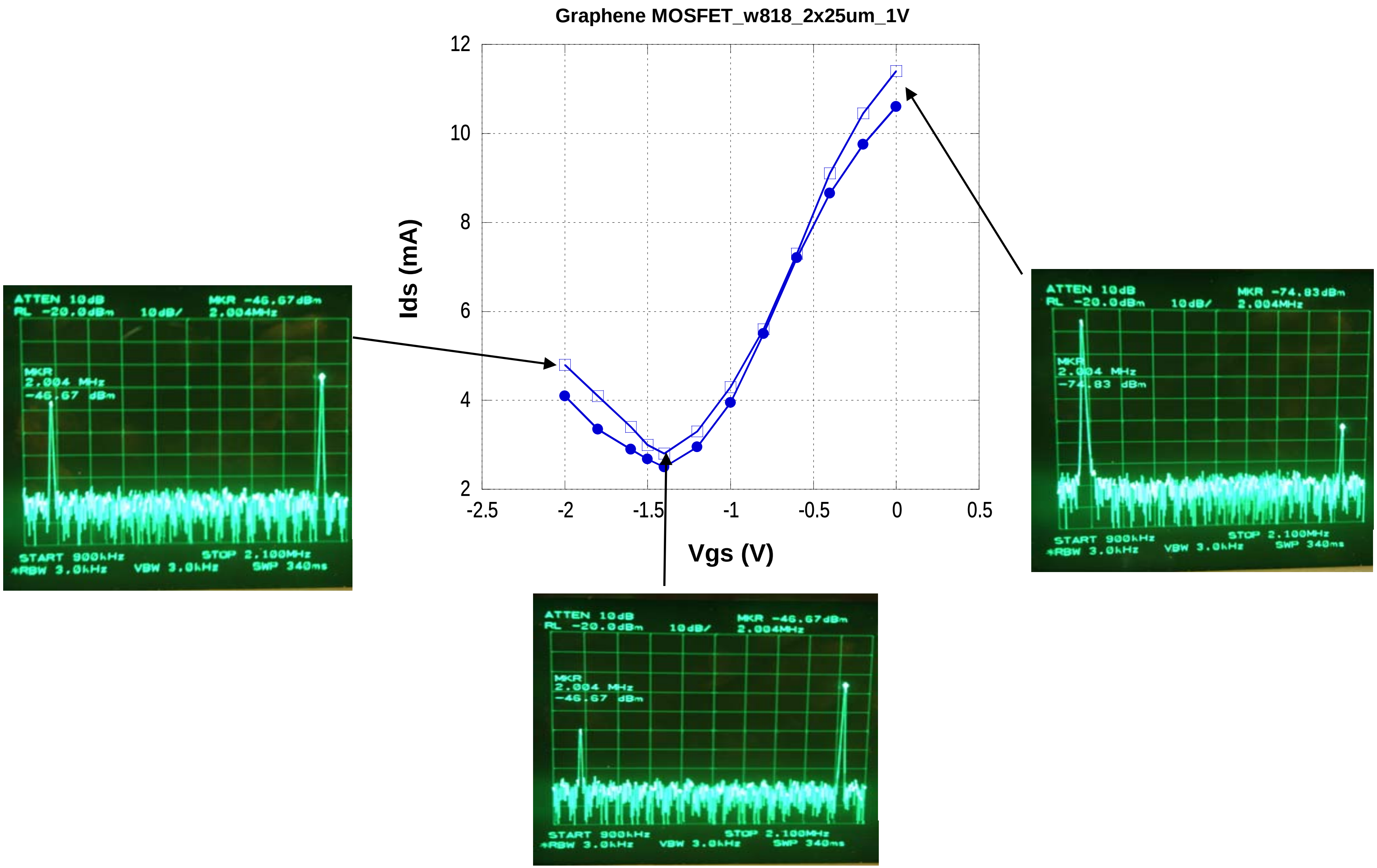


Unwanted reciprocal mixing phenomena

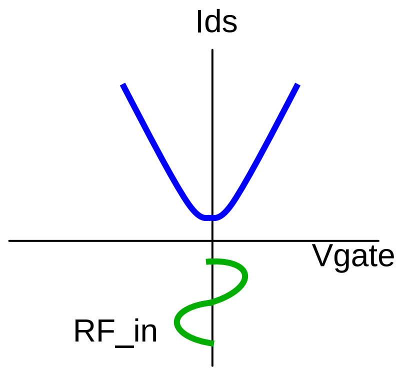


- Higher gm near the ambipolar point would offer mixer operation with reduced LO power and LO phase noise consequently.
- Improve mixer efficiency
- Reduce unwanted reciprocal mixing in electronic warfare environments
- Improve phase-noise limited mixer dynamic range

Graphene Frequency Multiplication

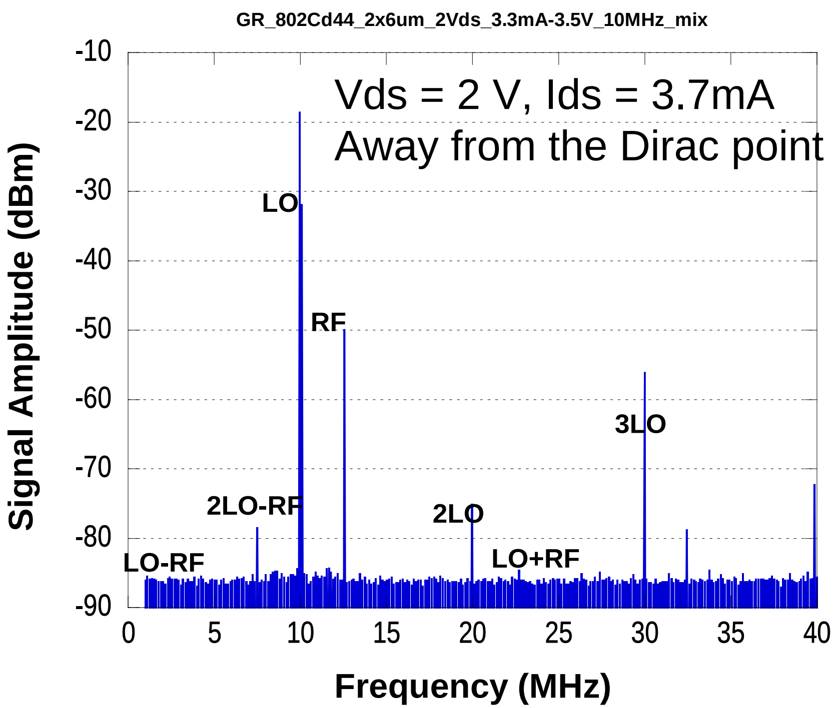


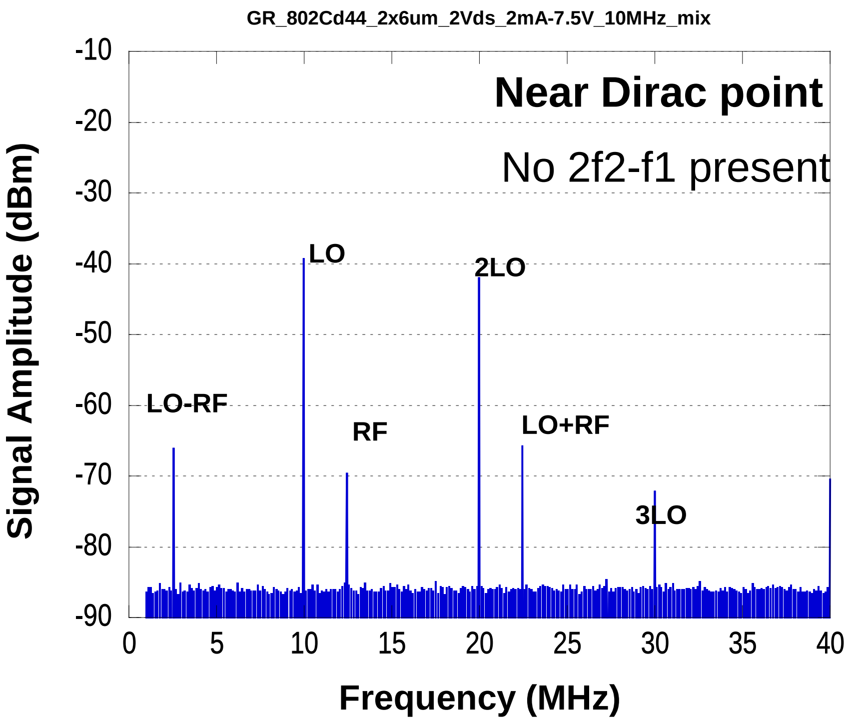
Graphene Frequency Mixing



$I \approx \beta V^2$

Potentially offer high dynamic range in mixing



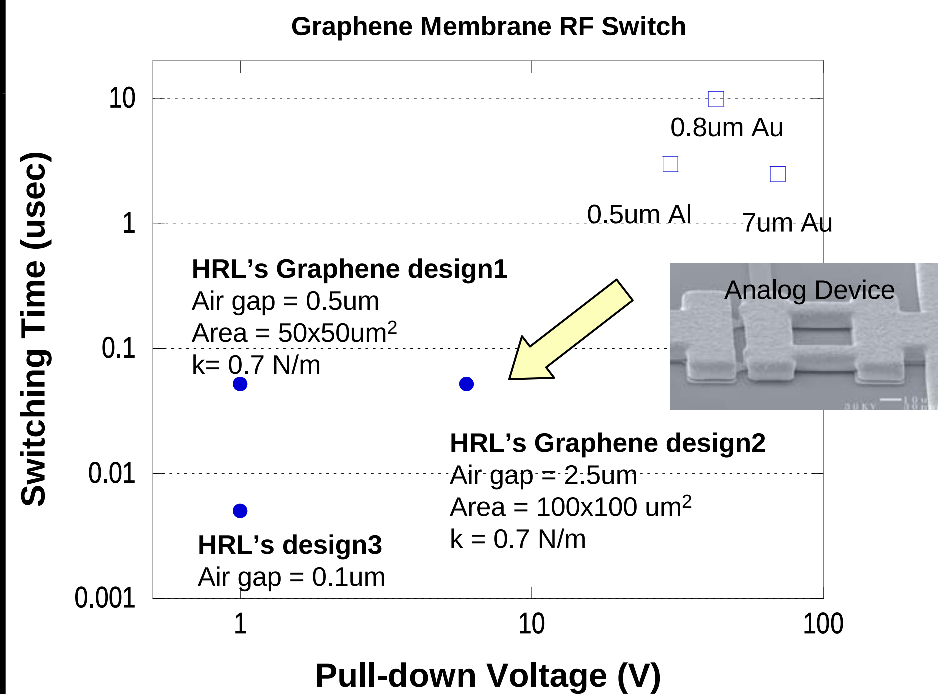


Graphene NEMS: Fast & Linear RF Switches

RF systems such as phased-array-radars need signal routing with fast, linear and low-loss capability.

$$\tau = 3.67\frac{V_p}{V_s\omega} = 3.67\frac{V_p}{V_s}\sqrt{\frac{m}{k}}$$

	FET or PIN	MEMS	Graphene
Insertion loss	> 1dB	<0.2 dB	<0.2 dB
Isolation	< 25dB	>30 dB	>30 dB
Linearity	Nonlinear	Linear	Linear
Speed	~10nS	~uSec	~5nS
Operation voltage	a few V	30-70V	1-5V
Reliability	High	Medium (due to sticking)	tbd



- **Offer a fastest (GHz) RF switch with low (1V) actuation voltage.**
- **Enable integration with CMOS, III-V ICs.**
- **Offer an integrated electronic-NEMS.**

Very-large Scale Active Flexible Electronics

Flex graphene
HRL, 2009

Key metrics for active flexible electronics

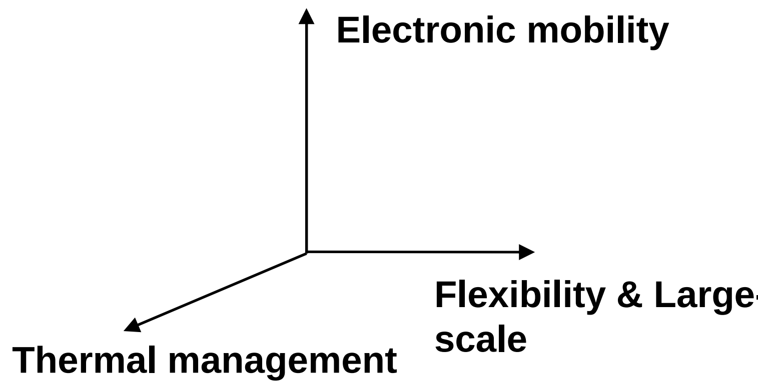
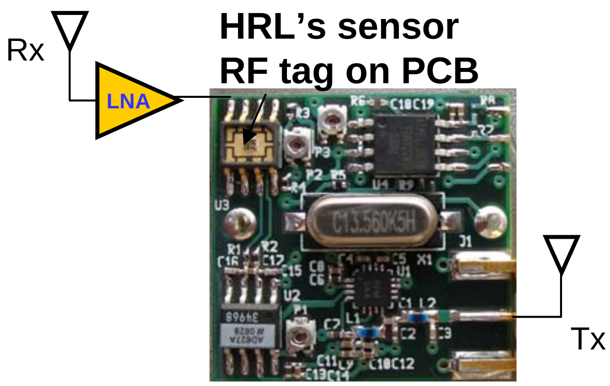


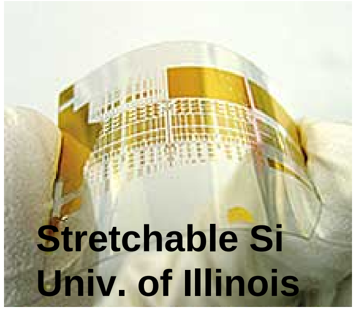
Table 1. Flexible Electronic Material comparison

Material	Field-effect Mobility (cm^2/Vs)	Thermal Conductivity (W/mK)	High-speed	Cost performance
a-Si:H	<1	< 5		
Pentacene	1.5	0.48	good	good
a-In-Ga-Zn-O	6-9	<1		
Si nano-membrane			poor	poor
Graphene	1000 -10000	5000	30-inch	good

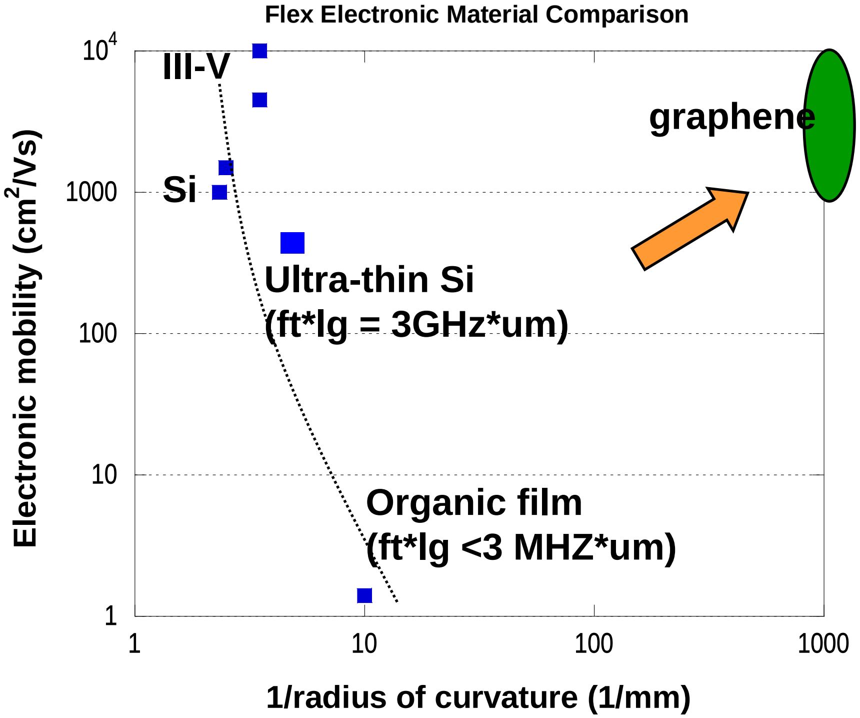
Very Large Scale Active Flexible Electronics

Fundamental physical limit: Strain = thickness/(2*radius of curvature)





- Monolayer-thick graphene can be only material form with 4-5 order-of-magnitude higher flexibility while maintaining high material quality, in principle.

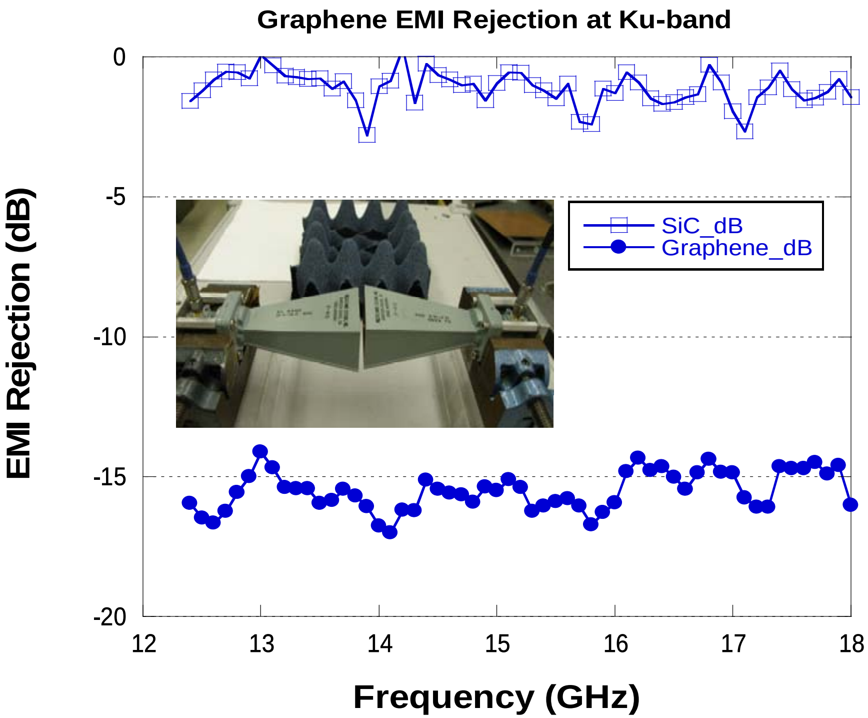


Potential Applications of Graphene

Some other applications

- EMI
- Non-volatile memory
- Cooling
- Harsh environment
- THz
- Thermoelectric
- Chem sensors
- Bioelectronics

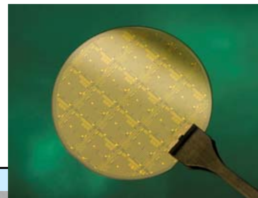
Transparent and EMI shielding



Graphene as Emerging Material

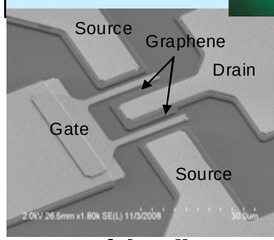
2008

A world's first
2" graphene MOSFET
(HRL)



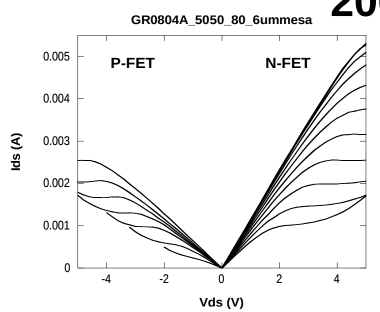
SOA Graphene FET:
gm = 770 mS/mm,
Ion/Ioff = 33
FET mobility~ 6000 cm2/Vs
(HRL, 2009)

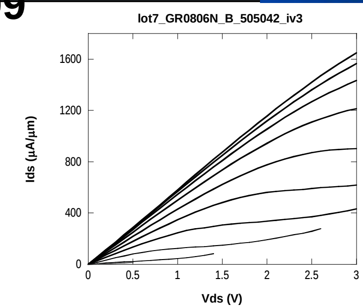
A world's first
3" graphene-on-Si
MOSFETs
(HRL, 2009)



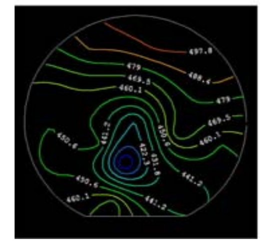
A world's first
Epitaxial
graphene RF-FET
(HRL, Dec, 2008)

2009



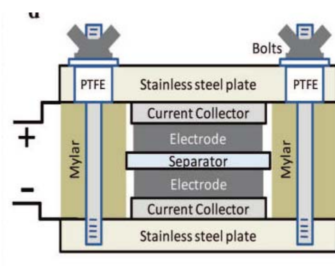


2010

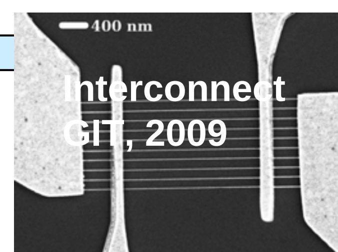


75mm
graphene-on-
SiC wafer
(HRL)

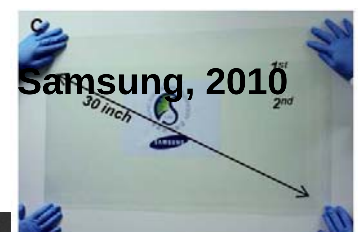
UT Dallas, 2008



Flexible graphene
HRL, 2009



Interconnect
GIT, 2009



Samsung, 2010