2D Materials for 3D Devices... and systems?

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University of Siegen

Young, medium-sized University
• Founded in 1972
• Restructured in 2011
• Students: 18,500
• Staff: 1,500

School of Science and Technology
100 faculty members
6000 students
Fostering interdisciplinary research
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GRADE
Graphene-based Devices and Circuits
for RF Applications

M-EraNet
NanoGraM

Title: Mashoff, Lemme, Morgenstern, Nano Letters 2010
Graphene and other 2D materials:

- Flexible
- High relative absorption
- Large scale production (CVD)
- Ultra broad band spectral response (graphene)
- Low absolute absorption
Graphene Photodetectors

- Performance requirements: high sensitivity, low noise, **wide band width**, high reliability and **low cost**
Graphene Photodetectors

- Vertical device architecture

Riazimehr, Lemme, ULIS, 2015
See also: Chen et al., Nano Letters, 2011
An et al., Nano Letters, 2013
Graphene Photodetectors

- Shockley equation:
  \[ I = I_S \left[ \exp \left( \frac{qV_d}{n k_B T} \right) - 1 \right] \]
- Ideality factor \( n = 1.52 \)
- Barrier height \( \Phi_b = 0.66 \text{ eV} \)
- \( p \) doping due to exposure to ambient atmosphere

Riazimehr, Lemme, Solid State Electronics, 2015
Graphene Photodetectors

Graphene/ n-Si photodiode

Calibrated Si photodiode

24 April 2015

NSF EU Workshop on 2D Materials - Arlington, VA
Si / MoS$_2$ Photodetectors

- High light absorption (5-10%) in visible range
- Monolayer MoS$_2$ - direct band gap of 1.8 and 2 eV
- N-type semiconductor
- Here: multilayer CVD grown MoS$_2$ on p-type silicon
- 8.26 nm thick n-MoS$_2$ (~ 12 layers)

See also: Lopez-Sanchez, Kis, ACS Nano, 2014
Si / MoS$_2$ Photodetectors

Spectral response measurement

Bulk MoS$_2$

\[ \begin{align*}
\text{p-Si:} & \quad 1.07 \text{ eV (1158 nm)} \\
\text{MoS}_2 : & \\
\Sigma_M - \Gamma_V & = 1.43 \text{ eV (867 nm)} \quad 1.3 \text{ eV} \\
K_M - K_{V1} & = 2.15 \text{ eV (576 nm)} \quad 1.8 \text{ eV} \\
K_M - K_{V2} & = 2.48 \text{ eV (500 nm)} \quad 2 \text{ eV}
\end{align*} \]

\{ \text{blue-shift 0.13 eV} \quad \text{blue-shift 0.4 eV} \}

Si / MoS$_2$ Photodetectors

Interlayer spacing

- $\Delta(\Sigma_m - \Gamma_V) = 1.43$ eV (867 nm)
- $\Delta(K_m - K_{V1}) = 1.3$ eV
- $\Delta(K_m - K_{V2}) = 1.8$ eV

Lattice spacing

- $\Sigma_m - \Gamma_V = 1.43$ eV (867 nm)
- $K_m - K_{V1} = 2.15$ eV (576 nm)
- $K_m - K_{V2} = 2.48$ eV (500 nm)

- 4% compressive strain
- confirmed by TEM analysis
- CVD materials ≠ exfoliated materials

A new proposal: Graphene Base Transistor - GBT

- “Hot Electron” transistor (C. Mead, 1960s)
- Charge carriers are transported perpendicular to the graphene sheet
- Operation depends on quantum mechanical tunneling
- Speed limit set by transport through base (here: 0.35nm monolayer!)
- Optimal resistance/thickness ratio

Mehr et al, IEEE EDL, 33(5), 2012
Vaziri et al, Nano Letters, 13, 2013
Graphene Hot Electron Transistors

Device Characteristics (GBT mode)

$V_B = 0...6 \text{ V}$

$V_C = 8 \text{ V}$

$V_E = 0 \text{ V}$

Base voltage sweep

Off-state

Collector Current $J_C$ (nA/cm$^2$)

$V_E = 0 \text{ V}$

$V_C = 8 \text{ V}$

EBI: 5 nm SiO$_2$

BCI: 21 nm Al$_2$O$_3$

On-state

Vaziri et al, Nano Letters, 2013
THz Operation seems feasible

- GBT are less sensitive to high injection effects than HBTs
- THz operation can be reached by intrinsic GBTs with different designs [Di Lecce, ESSDERC 2014]

Graphene-based Devices and Circuits for RF Applications

www.grade-project.eu
Graphene Fabrication Methods: CVD

Chemical vapor deposition (CVD)

- Catalytic growth on Ni, Cu, Ru, Ir, TiC, Ta...
- Process Temperatures: 850-1000°C
- Transfer to random substrates
- Transfer process
- High potential for large areas (R2R)
- Monolayer vs. multilayer control (solubility)
- Quality (grain boundaries, defects etc.)

CVD process on copper substrate

Kataria et al, pss b, 2014
Challenge: Process Integration

Transfer to manufacturability

• CVD is solved
• Transfer is solved
  • ...or is it?

• The CMOS spec:
  • Even very low concentrations ($10^{10} - 10^{11}$ atoms/cm$^2$) trace metals pose a serious threat to Si devices.
  • Contamination is often investigated with X-Ray Photoelectron Spectroscopy (XPS)
  • XPS does not provide the required resolution to detect trace elements.

Smith et al, Solid State Electronics, 2015
Challenge: Process Integration

Transfer to manufacturability

The approach:

- Time-of-flight secondary ion mass spectrometry (ToF-SIMS) and
- Total reflection x-ray fluorescence (TXRF) →

  - Elemental fingerprints of residual contamination with a sensitivity better than $10^9$ atoms/cm$^2$.

ToF SIMS $^{63}$Cu$^+$ and $^{56}$Fe$^+$ maps on the corner of a graphene layer on SiO$_2$.

Lupina et al., ACS Nano, 2015
Challenge: Process Integration

Transfer to manufacturability - Contamination remains a serious issue

Lupina et al., ACS Nano, 2015

BUT: Kauschik et al., Solid State Technology, 2015
Bias-temperature instability in single-layer graphene FETs

- Established methodology
- 2 Gaussian distributions in Si technology to describe NBTI recovery
- Second distribution assigned to dangling bonds is absent in GFETs
- “Behaves like very early high-k”

IIlarionov, Lemme, Grasser, APL, 2014
Challenge: Circuit Design

Compact Model to Process Design Kit

- Established compact model

GFET VerilogA model and simulation results using Spectre

Fregonese, Happy, Zimmer, IEEE TNano, 2013
Rodriguez, Lemme, IEEE TED, 2014
Graphene based custom IC after fabrication

Challenge: Circuit Design

Circuit design

Layout generation

See also: Kaustav Banerjee
Challenge: Circuit Design

- Design kit developed by GRADE available for download in 10/2015
- Will be public domain
- Details to be disclosed at ESSDERC/ESSCIRC 2010 Tutorial in Graz, Austria (European Solid-State Device / Circuit Research Conference)
Summary

• 3D may be the way to go for 2D

• High responsivity in graphene / silicon photodiodes

• Spectral response measurements to probe the material properties

• Vertical hot electron transistors: high performance devices?

• Challenges towards higher TRLs will require long term efforts

Thank you for your attention!