Detection of Ionizing Radiations with Graphene Field Effect Transistors (GFET)

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Introduction & Background

Radiation detection has been very closely coupled with advances in semiconductors.

How Can graphene do it (well)?
Radiation Detection

SNM/FM Radiation Sensing --- some state of art: High Resolution is Desirable

- HPGE (High Purity Ge)
  [charge collection]
- Superconductor TES (Transition Edge Sensor)
  [NOT charge collection; use a *sharp feature*]

Can we have a *sharp feature* @ ~ room $T$ that couples to radiation(effect)
What is Graphene

- (electrically isolated) “discovered” in 2004
- Building block of many carbon (nano)materials
- New “wonder” semiconductor/semimetal
- Amazing Electrical Properties – (“post Si” electronics/”Moore”)
- Amazing Mechanical Properties – highest strength (~CNT)
- Amazing Thermal properties – highest thermal conductivity
- Easy to make and work with (2D planar fabrication)

Electrons in graphene

\[ E = p v_F = \hbar k v_F \]

\[ v_F \sim 1 \times 10^6 \text{ m/s} \]

- Dirac equation
- Chiral massless fermions [QED/QCD in graphene]

- High conductivity/mobility (>10X Si @ room T)
- Low (electronic) noise
- Tunable (electr.) properties
- Exposed to environment --- excellent sensor mat.
**Sharp Electric Field Effect in Graphene GFET**

- **Finite R** (quantum R)
- **Low noise**
- **High mobility** (can ballistic)
- **High speed** [THz]
- **High sensitivity** [dE/E<10⁻³]
- Bandgap eng possible

... all these even at 300K

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"the sharp feature" with **low electrical noise** (even @ room T)

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F. Schedin et al'2007
GFET for radiation sensing

Graphene is a highly sensitive to detect local electric field change [single molecule sensitivity]

- Vgate tunable → sensitivity and resolution
- NOT relying on collecting/drifting ionized charges; appearance of ionized charges changes electric field
- sensing Efield intrinsically faster than sensing drifted/collectioned charges
- can work with variety of absorber substrates for gamma/neutron interaction; thin insulator layer
  [eg. Narrow bandgap semiconductors]

How well can GFET detect radiation [rare events]

Sensitivity/energy resolution?
Preliminary Results

- Modeling of radiation-material interaction; Modeling of possible radiation detection schemes using graphene-based sensors
- Fabricating/Developing/Characterizing suitable graphene-based materials and devices
- Proof of concept experiments with graphene field effect transistors: radiation responses; *local electric field* sensitivity
- Physico-chemical changes: studies of effects of charged-particles irradiation on graphene and GFET

GFET based radiation sensor
(eg. *sharp* change of resistivity due to *change* of *electrical field* caused by ionizing radiation)
Modeling: radiation-substrate (absorber) interaction

- MCNP and MCNP-Polimi modeling of interaction of ionizing radiation (gamma, neutrons) with absorber materials: various semiconductors (Si, Ge, InSb), polystyrene etc.
- Compton electron transport through substrate (CASINO)
- recently also started using Geant4 (M. Foxe et al)
COMSOL Modeling:
GFET response to radiation ionized charges

Local electric field effect

Gabe Lopez et al.,

Simplified model with straight tracks --- good for neutrons?
GFET response to radiation ionized charges: Position Sensitive
Various possible detections schemes under investigation:
- remote detection FET (better for straight tracks/neutrons?)
- drift charges, but do not collect them → use graphene (as effective low noise amplifier to read out the charges (for gammas?) or a “trans-photoconductor”
- …
Material/Device Fabrication of Graphene and GFET

“exfoliation” (scotch tape)

Graphene on doped Si with 300 nm oxide

E-beam lithography

Develop PMMA

Cr/Au evaporation

Lift off

Lithography → Nanodevices

Doped Si

SiO₂

PMMA

Cr/Au

Photo by Sambandamurthy
How to identify graphene

Optical microscopy -- seeing is believing

Raman Spectroscopy
(also sensitive to defects in graphene)

Quantum Hall Effect
(magnetoresistance)

I. Childres et al (see poster 3)
GFET Characterization

Semiconductor=Si
Insulator=300nm SiO2

Want: high-mobility graphene
[sharp FET]
Large-scale Graphene Available by CVD

Quantum Hall Effect

$h/2e^2$

• Fabricating Graphene on other absorbers: Ge

(w/t 30nm germanium oxide)
Proof of Concept: Photo-actuated GFET

Also tried photo-resistor similar to photodiode
Also tried MOSFET

G.Lopez et al.

Experiments currently underway with
• undoped Si-substrate
• hospital X-ray source
• 82mC gamma source
Local Field Effect: by Side Gate

Graphene is sensitive to \textit{local} electric field

J. Tian et al.,
Local Electric Field Effect by AFM tip

R. Jalilian et al. (2009)
Charged-particles irradiation: e-beam

effect of energetic charged particles (eg. electrons)
also relevant for (long term) reliability of GFET radiation sensors

30keV electron beam
I= 0.15nA; Time=5mins; Expose area: 50um x 50um
Estimated dose: 112.5 e-/nm²

e- beam adds to graphene negative (n-) charges

(I.Childres et al)
Charged-particles irradiation: O+ ions

O+ ions generated in a “microwave” plasma chamber

O+ ions add to graphene positive (p+) charges

Defect creation studied also by:
Raman spectroscopy
AFM (atomic force microscopy)
time-dependent behavior

I. Childres et al., in preparation

These studies also relevant for rad-hard graphene electronics!
Summary

Graphene sensors for SNM radiation ($\gamma/n$) detection
• compatible with a wide variety of absorber materials
• NOT drifting/collection charges
• based on **sharp** field effect
• exciting promises:
  high speed, high sensitivity,
  excellent energy resolution, room $T$
• potentially opening a new approach for radiation detection

**Initial results --- focus on proof-of-concept**
• Modeling/design of graphene FET radiation sensor
  MCNP/CASINO modeling of $\gamma/n$-substrate interaction
  COMSOL modeling: demonstrate GFET response to radiations
• Fabricating/testing graphene & GFET (graphene field effect transistor)
  high quality graphene material fabricated
  demonstrated laser-irradiation actuated GFET
• charged-particle irradiation on graphene/GFET
  effects of $O^+$ ions & e- beams demonstrated reliability of GFET radiation sensors

**On-going/future work**
• fabricate/test GFET on a variety of absorbers: Si, Ge, InSb, CZT, ...
• radiation response experiments
  gamma rays
  neutrons
  alpha/beta etc
• graphene radiation detector:
  study energy resolution, sensitivity, speed etc.
  detector design, architecture and integration
• graphene composite
  (physico-chemical approach)