The IEEE Microwave Theory and Techniques Technical Committee (MTT-25)
RF Nanotechnology
Mission and Perspectives
in the European Area

Luca Pierantoni, Università Politecnica delle Marche, Ancona, Italy,
l.pierantoni@univpm.it
MTT-25 Chair

Fabio Coccetti, LAAS-CNRS Toulouse, France, coccetti@laas.fr,
MTT-25 Vice-Chair

(http://mtt.org/index.html)
Outline

- The IEEE MTT-25 RF Nanotechnology Technical Committee (mission, goals, topics)

- MTT-25 Worldwide Activities
  - Conferences, workshops, special sessions, meetings, publications
  - High relevance of research activities of the MTT-25 members

- Perspectives in the European Area
  - focusing research areas
  - defining routes
  - on Radio-Frequency nanotechnology/nanoelectronics

- Research Activity at the Università Politecnica delle Marche, Ancona, Italy
The IEEE MTT-25 RF Nanotechnology Technical Committee

- Reason for being
- Mission
- Membership
- Topics
The Microwave Theory and Techniques is the largest IEEE Society
more than 11000 members worldwide

The core purpose of the Society is to foster the advancement and application of RF and microwave theory and techniques

...inside MTT, no technical committee focused the area of nanotechnology/ nanoelectronics

...prompted by the axiom that RF/microwave technology will be fundamentally influenced by nanotechnology, after some years of initiatives (conferences, workshops etc...)

...we formed a new Technical Committee, MTT-25, RF Nanotechnology, approved on January 2010 by the MTT AdCom
Reasons for Being

- nanotechnology/nanoelectronics has the potential to introduce a **paradigm shift** in electronic systems design similar to that of the transition from vacuum tubes to semiconductor technology.

- nano-materials and nano-devices often exhibit their most interesting properties on a **broad range of frequencies**, through microwaves up to THz.

- due to its involvement in
  - basic research,
  - novel applications
  - design
  - measurement techniques
  - strong relations with the industry engaged in nanoelectronics and new material (e.g., the semiconductor industry)

...the MTT community is eminently positioned to assimilate the multidisciplinary nature of RF nanotechnology.
Mission

- The main goal is to provide an appropriate venue to review perspectives and foster innovation in the area of nanotechnology and nanoelectronics that are of the most interest
  - to the MTT engineering community
  - ... but also to an enlarged scientific and technological community, from nanosciences to industry
- foster the transition from the research labs to the relevant industry
- to interface with well-recognized international councils responsible for defining standards and finding routes in RF nanoelectronics such as
  - International Technology Roadmap for Semiconductors (ITRS)
  - IEEE Nanoelectronics Standards Roadmap
  - IEEE Nanotechnology Council (NTC)
  - the European Community (in the European Area)
MTT-25 members involve engineers, physicists, chemists
active group and open forum defining scientific topics, fostering publications, organizing events, participation in projects

<table>
<thead>
<tr>
<th>Name</th>
<th>Institution</th>
<th>Email Address</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luca Pierantoni (Chair)</td>
<td>UPM –Italy</td>
<td><a href="mailto:l.pierantoni@univpm.it">l.pierantoni@univpm.it</a></td>
</tr>
<tr>
<td>Fabio Coccetti (Vice-Chair)</td>
<td>LASS-CNRS –France</td>
<td><a href="mailto:coccetti@laas.fr">coccetti@laas.fr</a></td>
</tr>
<tr>
<td>Peter Russer</td>
<td>TUM – Germany</td>
<td><a href="mailto:russer@tum.de">russer@tum.de</a></td>
</tr>
<tr>
<td>Paolo Lugli</td>
<td>TUM – Germany</td>
<td><a href="mailto:lugli@tum.de">lugli@tum.de</a></td>
</tr>
<tr>
<td>Mircea Dragoman</td>
<td>IMT- Romania</td>
<td><a href="mailto:mircea.dragoman@imt.ro">mircea.dragoman@imt.ro</a></td>
</tr>
<tr>
<td>Robert Plana</td>
<td>LAAS-CNRS – France</td>
<td><a href="mailto:plana@laas.fr">plana@laas.fr</a></td>
</tr>
<tr>
<td>Adrian M. Ionescu</td>
<td>EPFL – Switzerland</td>
<td><a href="mailto:adrian.ionescu@epfl.ch">adrian.ionescu@epfl.ch</a></td>
</tr>
<tr>
<td>Luca Roselli</td>
<td>Uni PG – Italy</td>
<td><a href="mailto:rossell@diei.unipg.it">rossell@diei.unipg.it</a></td>
</tr>
<tr>
<td>Marco Farina</td>
<td>UPM - Italy</td>
<td><a href="mailto:m.farina@univpm.it">m.farina@univpm.it</a></td>
</tr>
<tr>
<td>Tullio Rozzi</td>
<td>UPM – Italy</td>
<td><a href="mailto:t.rozzi@univpm.it">t.rozzi@univpm.it</a></td>
</tr>
<tr>
<td>Stephen Purcell</td>
<td>UMR-CNRS –France</td>
<td><a href="mailto:stephen.purcell@univ-lyon1.fr">stephen.purcell@univ-lyon1.fr</a></td>
</tr>
<tr>
<td>Christophe Caloz</td>
<td>EPM –Canada</td>
<td><a href="mailto:christophe.caloz@polymtl.ca">christophe.caloz@polymtl.ca</a></td>
</tr>
<tr>
<td>Manos M. Tentzeris</td>
<td>GaTECH –USA</td>
<td><a href="mailto:etentze@ece.gatech.edu">etentze@ece.gatech.edu</a></td>
</tr>
<tr>
<td>George W. Hanson</td>
<td>UWI – USA</td>
<td><a href="mailto:george@uwm.edu">george@uwm.edu</a></td>
</tr>
<tr>
<td>Peter Burke</td>
<td>UCI – USA</td>
<td><a href="mailto:pburke@uci.edu">pburke@uci.edu</a></td>
</tr>
<tr>
<td>Tomas Palacios</td>
<td>MIT – USA</td>
<td><a href="mailto:tpalacios@mit.edu">tpalacios@mit.edu</a></td>
</tr>
<tr>
<td>Wolfgang Porod</td>
<td>ND – USA</td>
<td><a href="mailto:porod@nd.edu">porod@nd.edu</a></td>
</tr>
<tr>
<td>Stephen Goodnick</td>
<td>ASU USA</td>
<td><a href="mailto:stephen.goodnick@asu.edu">stephen.goodnick@asu.edu</a></td>
</tr>
<tr>
<td>Dimitrios Peroulis</td>
<td>Univ Perdue – USA</td>
<td><a href="mailto:dperouli@purdue.edu">dperouli@purdue.edu</a></td>
</tr>
<tr>
<td>Goutam Chattopadhyay</td>
<td>NASA – USA</td>
<td><a href="mailto:goutam@jpl.nasa.gov">goutam@jpl.nasa.gov</a></td>
</tr>
<tr>
<td>Erping Li</td>
<td>IHPC – Singapore</td>
<td><a href="mailto:eplee@ihpc.a-star.edu.sg">eplee@ihpc.a-star.edu.sg</a></td>
</tr>
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MTT-25 Members
European Symposium on Carbon-based Electronics

Carbon nanotubes (CNT), graphene and nanowire (NW) circuits
Nano-structured microwave metamaterials
Nano-wireless sensors and power meters
Nano antennas and arrays
THz nano-electronics/photonics
Nano-interconnects for advanced RF packaging
Nanoscale electro-mechanical switches (NEMS) and resonators
Spintronics and molecular electronics
Nano-particles and nano-plasmonic structures
Superconducting nanostructures, RF nanodevices for quantum information processing

Theoretical Issues and Modeling

- Multiphysics modeling of nanostructures and nano-devices
- Ballistic transport, periodic modes, multiport circuits in nano-materials
- Advanced techniques for the electromagnetic/coherent-transport problem
- Electrodynamics, field emission, radiation, detection photo-generation
- Wave mixing, dispersive- and non linear-effects in nano-materials

Technology, Instrumentation, Imaging and Reliability

- Metrology and of nanoscale devices/systems
- Microwave nanoscale near field imaging and surface patterning
- Noise measurements of nanoscale devices
- CMOS compatibility and 3D-integration of carbon- and silicon/semiconductor-based nanodevices
One of the main research stream of MTT-25
Graphene RF Electronics

Graphene is quickly becoming an extremely interesting option for a
wide variety of RF electronic devices and circuits

- FET
- Interconnects
- Low-noise amplifiers
- Nonlinear electronics

✓ outstanding performances
✓ with much lower power draw
✓ processing technology compatible to
✓ that used in advanced silicon device
✓ fabrication (CMOS)
Graphene: the amazing nanomaterial

✓ Thinnest material sheet imaginable...yet the strongest! (5 times stronger than steel and much lighter!)
✓ Graphene is a semimetal: it conducts as good (in fact better!) than the best metals, yet its electrical properties can be modulated (it can be switched ON and “OFF”)
✓ Superb heat conductor
✓ Very high current densities (~10^9 A/cm^2)

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Silicon</th>
<th>AlGaAs/InGaAs</th>
<th>InAlAs/InGaAs</th>
<th>SiC</th>
<th>AlGaN/GaN</th>
<th>Graphene</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron mobility at 300K (cm^2/V·s)</td>
<td>1500</td>
<td>8500</td>
<td>5400</td>
<td>700</td>
<td>1500-2200</td>
<td>&gt; 100,000</td>
</tr>
<tr>
<td>Peak electron velocity (× 10^7 cm/s)</td>
<td>1.0 (1.0)</td>
<td>1.3 (2.1)</td>
<td>1.0 (2.3)</td>
<td>2.0 (2.0)</td>
<td>1.3 (2.1)</td>
<td>5-7</td>
</tr>
<tr>
<td>Thermal conductivity (W/cm·K)</td>
<td>1.5</td>
<td>0.5</td>
<td>0.7</td>
<td>4.5</td>
<td>&gt;1.5</td>
<td>48.4-53</td>
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Graphene field-effect-transistors: Excellent candidate for high frequency electronics
The research activities of the MTT-25 members is of high relevance and impact in the worldwide panorama.
RF graphene transistor with a cut-off frequency of 100 GHz

Dr. Yu-Ming Lin

Graphene 100-GHz device fabricated on graphene/SiC wafer (the scale bar is 2 µm) at the IBM T.J. Watson Research Center, Yorktown Heights, New York,
Carbon Based RF Electronics

Some Comparison

<table>
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<tr>
<th>Technology (material)</th>
<th>$f_T \cdot L_G (GHz \cdot \mu m)$</th>
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<tbody>
<tr>
<td>Graphene FET (IBM)</td>
<td>24</td>
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<tr>
<td>InP HEMPT</td>
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<tr>
<td>Si/SOI (90nm)</td>
<td>11</td>
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<tr>
<td>ITRS n-MOS</td>
<td>9</td>
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Demonstrated the world’s fastest RF devices

- Transferred graphene with $f_T > 50$ GHz
- Epi-graphene with $f_T$ as high as 100 GHz

Y.M. Lin – IBM (IMS 2010)
a research route is Graphene Ambipolar Electronics

The ambipolar properties of graphene enable a vast array of new RF devices:

- **Graphene FET (GFET) for THz:**
  - High mobility and carrier velocity
  - Excellent electrostatic control

- **GFET frequency multipliers:**
  - High spectrum purity ~94% and low noise without filtering demonstrated at 1.4 GHz

- **GFET zero-volt RF detector:**
  - High efficiency detector and energy harvesting devices

- **GFET mixers:**
  - High efficiency and low intermodulation distortion

- **Graphene circuits:**
  - Radio demodulators, analog-to-digital converters

Graphene Frequency Multipliers

Application Circuit

Input and output waveform with $f_{in}=700$ MHz and $f_{out}=1.4$ GHz

Output power spectrum with $f_{in}=700$ MHz and $f_{out}=1.4$ GHz

>90% of RF output power is in the 2\textsuperscript{nd} harmonic without the need of any filtering element

tpalacios@mit.edu
Graphene Mixers and BPSK

GFET Ambipolar Mixers

GFET Binary Phase Shift Keying (BPSK)

Measured Output Spectrum

\[ f_{\text{RF}} - f_{\text{LO}} \]
\[ 2f_{\text{RF}} - 2f_{\text{LO}} \]
\[ f_{\text{LO}} - f_{\text{RF}} \]
\[ 2f_{\text{LO}} - f_{\text{RF}} \]

Measured Waveform

Carrier Signal
\[ f_c = 500 \text{ Hz} \]

Data Signal
\[ d = 50 \text{ Hz} \]

Output Signal

\[ k_1(t) = A_c \cos(2\pi f_c t) \quad 0 \leq t \leq T \text{ if binary data is '1'} \]

\[ k_2(t) = -A_c \cos(2\pi f_c t) \quad 0 \leq t \leq T \text{ if binary data is '0'} \]

tpalacios@mit.edu
Toward RF Nanosystems

Digital and FM radio demodulator using suspended single wall carbon nanotube resonators in the field effect transistor configuration, realized at the Laboratoire de Physique de la Matière Condensée et Nanostructures Université Lyon, by Dr. Stephen Purcell (MTT-25 member)
Worldwide Activities of MTT-25

- provide technical articles in MTT publications
- promote and sponsor special issues of MTT-S publications
- promote, endorse, organize, and review proposals at the annual IMS, EuMW, APMC
- workshops; focused, special, and panel sessions; and tutorials
- support regional and other technical meetings
- collaborate with other TCs of the MTT-S, as well as with technical program committees of international
- and national conferences of interest to the MTT-S and its members
Workshop

New Microwave Devices and Materials Based on Nanotechnology

Focused Session

The Impact of Nanoelectronics on Radio Frequency Technology
next events

- Workshop “Nanotechnologies: the Gateway to Innovative Radio Frequency Devices”
- Focused session “Nanointerconnects for Advanced RF Packaging”

APMC 2010: Asia Pacific Microwave Conference (Yokohama, Japan, Dec. 2010)
- Invited Talk “Overview on the impact of Nanotechnologies on the RF/Microwave technology”
Publications

“Special Issues” on “RF Nanoelectronics” are being planned for:

- IEEE Microwave Magazine, December 2010
- IEEE Microwave Magazine, 2011
- IEEE Microwave Theory and Techniques, 2011

Submissions from physicists and chemists are WELCOME !!!
IEEE Transactions on Microwave Theory and Techniques

Special Issue on
Radio-Frequency Nanoelectronics

- call for paper – June 2010
- deadline – December 30, 2010
- publication date – June 2011

Guest Editors
- Luca Pierantoni, Università Politecnica delle Marche, Ancona, Italy
- Fabio Coccetti, LAAS-CNRS Toulouse, France
- Paolo Lugli, Technische Universität München, Germany
- Stephen M. Goodnick, Arizona State University, AZ, USA

http://www.mtt.org/announcements.html

Please, SUBMIT and ENDORSE submissions !!!
IMS 2011 Baltimore, June 5-10 – 2011
new technical area
RF Nanotechnology

deadline – Dec. 3, 2010

Agenda 2011: planned events

- Special Session in the“11th Silicon Monolithic Integrated Circuits for RF Systems” (SiRF) Phoenix, Arizona , Radio Wireless Week (RWW) 2011

- Focused Session in the 27th International Review of Progress in Applied Computational Electromagnetics Conference, the Applied Computational Electromagnetics Society (ACES), Williamsburg, VA, 2011

- Special Session in the 30th URSI General Assembly and Scientific Symposium (XXXth URSI GA), 2011, Istanbul, Turkey

- we are organizing a special session in the most important international conference on graphene (Bilbao, April 2011)
further proposals for 2011

- Asia-Pacific Microwave Conference 2011 (APMC) 
  Melbourne
- EuMA 2011 - Manchester

- Workshop /focused session
- Computational Nanoelectronics
- Nanotechnology for Space Applications
- CNT nanoelectronics
upcoming actions

- new members coming from industry are going to be involved
- in MTT-25 (IBM, Samsung, NEC, Intel)
  - bringing complementary skills
  - focusing industrial technologic problems (e.g. internconnects)

Goal: roadmap of RF applications

- MTT-25 should try to finding and defining routes in the
  - Radio-Frequency applications of nanoelectronics/nanotechnology
  - from carbon-devices to wireless sensor network

- We are writing MTT-25 document to submit to
  - International Technology Roadmap for Semiconductors (ITRS)
  - EC for EU actions (a public consultation is open)
future activities

- a IEEE Journal on RF Nanotechnology/Nanoelectronics
  - papers on this topic are now scattered among many journals, most of which are not IEEE journals
  - there is no journal IEEE or not IEEE, that clearly address the RF applications of nanotechnology

- …or a IEEE Letter
  - …with very fast submission-to-publication cycle
  - rapid communications of results
  - the Letter will be endorsed by the IEEE Electron Device Society
  - and by the IEEE Nanotechnology Council (NTC)
Perspectives of MTT-25 in the European Area

- facing and interacting with the EC for defining projects in the area of RF nanotechnology
- submit a document dealing with the impact of nanotechnology on RF technology
- to co-organize a topical Meeting (a crossover among chemists, physicists, and engineers) inviting people
- European part of MTT-25: endorsement and participation to projects and other activities
MTT-25: Mission and Perspectives in the European Area

Luca Pierantoni (Chair)  
Tullio Rozzi  
Marco Farina  
Luca Roselli  
Fabio Coccetti, (Vice-Chair)  
Robert Plana,  
Stephen Purcell,  
Peter Russer,  
Paolo Lugli,  
Mircea Dragoman  
Adrian M. Ionescu,  

Università Politecnica Marche, DIBET, Ancona –Italy  
Università Politecnica Marche, DIBET, Ancona –Italy  
Università Politecnica Marche, DIBET, Ancona –Italy  
Università di Perugia (DIEI) – Italy  
Lab. Analysis Archit. Systems (LAAS), CNRS –France  
Lab. Analysis Archit. Systems (LAAS), CNRS –France  
Lab.de Phys.de la Mat. Cond.et Nanost. Université Lyon–France  
Technische Univ.Muenchen (TUM), Inst. Nanoelectronics – Germany  
Technische Univ.Muenchen (TUM), Inst. Nanoelectronics – Germany  
Scientific research and tech.development in microtech. (IMT), Bucarest- Romania  
Nanolab, Ecole Polytechnique Fédérable de. Lausanne (EPFL) –Switzerland

European branch of MTT-25

the European Institutions (universities, industries) involved in MTT-25, through its members, are keen to interact and participate to the definition of a European Network on Carbon-based Nanoelectronics

Technical Committee MTT-25  
RF Nanotechnology  
IEEE Microwave Theory and Techniques Society
European Institutions of MTT-25

What they do on Carbon-Nanoelectronics

- Università Politecnica Marche, Ancona –Italy (THEORY and MODELING of CARBON-NANODEVICES, AFM-NA)
- Università di Perugia (DIEI) – Italy (RFID SYSTEMS on CARBON-NANOMATERIAL)
- Lab.de Phys.de la Mat. Cond.et Nanost. Université Lyon–France (CNT RF DEVICES, NANORADIO)
- Tech.Univ.Muenchen (TUM), Inst. Nanoelectronics – Germany (CNT, RFID and MOLECULAR ELECTRONICS, QUANTUM INFORMATION PROCESSING)
- Scientific res. and tech. Dev. in microtech. (IMT), Bucarest- Romania (THEORY and MEASUREMENTS of CARBON DEVICES)
- Nanolab, Ecole Polytechnique Fédérale de. Lausanne (EPFL) –Switzerland (CNT TECHNOLOGY)

What they, jointly, can do

- possible definition of a European enlarged network
- proposing, defining and participating to projects
- other initiatives
  - topical meeting
  - Workshop, short courses
  - activation of training programs
Research Activity at the Università Politecnica delle Marche, Ancona, Italy
Recent developments in the broadband near-field Scanning Microwave Microscopy (SMM)

Prof. Marco Farina, Senior Member IEEE
Dipartimento di Bioingegneria, Elettronica e Telecomunicazioni

Università Politecnica delle Marche
Research Activity on Carbon-Devices Modeling

- Frequency domain analysis of quantum transport in CNT/GNR devices
  - MATLAB packages

- Full-wave time-domain model of the combined Maxwell/quantum transport in CNT/GNR devices
  - TLM-FDTD based packages
Analysis of CNT Transistors

multi-wall and multi-band coherent carrier transport

$$\frac{d^2 \Psi_{h,e}^{n,m}}{dz^2} = -\frac{2m_{h,e}^{n,m}}{\hbar^2} \left( E - U_{h,e}^{n,m}(z) \right) \Psi_{h,e}^{n,m}$$

$m$-th wall $n$-th sub-band

Schrödinger equations
Transmission Line approach

Poisson equation
FEM approach

The Schrödinger equation is written for each individual transport channel

$V$ is the electrostatic potential satisfying the Poisson equation
Poisson-Schrödinger system for a sw-CNT

Example of electronic transmittivity through a sw-CNT
(gate voltage=0.5V, drain-to-source voltage=0.2&0.4V)

Linear charge density along a sw-CNT vs drain voltage (gate voltage=0.5V)
Dynamic response of a mw-CNT (equivalent circuit)

\[
\frac{g_m}{(C_{SG} + C_{DG})} \left| \frac{1}{j\omega} \right| = 1 \quad \Leftrightarrow \quad \omega_T = 2\pi f_T = \frac{g_m}{(C_{SG} + C_{DG})}
\]

The unitary-gain-frequency: increases with the number of walls

Transconductance: increases with the diameter and/or the number of walls
Analysis of GNR

*\( \psi \): electronic wavefunction

Scattering, through a GNR “black box”, of modes injected at right and left ports.

Reciprocity \( \Rightarrow S = S^T \)

Absence of losses \( \Rightarrow S^+ S = I \)
Characterization of GNR

- approach to the charge transport based on scattering matrices
  - starting from the tight binding (TB) technique, electronic wavefunctions can be described as periodic guided modes
  - with respect to the basis of periodic modes, a scattering matrix can be defined; properties of charge conservation and reciprocity are expressed by:

\[
S^+ S = I \quad S = S^T
\]

- implemented algorithms for charge transport include:
  - multimodal case (wide GNR and/or high carrier energies)
  - multibranch GNR and junctions (n-port GNR circuits)
  - multilayer GNR (many graphene-layers interacting)
  - presence of external electric and magnetic fields
  - lattice defects and discontinuities

- the GNR-FET geometry and configuration constitutes the basic device for several applications, such as interconnects, LEDs and photovoltaic cells

Example 1: transmittivity through a semiconducting GNR across a vacancy defect, as a function of the energy.

Reflection is enhanced in correspondence of the cut-off energies of any mode.

Total transmittivity (all propagating modes injected) is the sum of the transmittivity of all propagating modes.

All energies are referred to the Fermi point.

Visual example of wavefunction scattered by a vacancy.

GNR width = 2.2nm.
Example 2: interference effects

Long structures containing many localized defects

Transmission through cascaded vacancies vs:
- carrier energy
- defects distance

In general, the effect of localized defects on carrier propagation is shown to be potentially quite strong.
Example 3: four port GNR circuit

the actual simulated structure consists of thousand atoms.

The circuit is made of two single-layer GNRs intersecting to a double layer GNR, with additional inter-layer energy connections.

wavefunction in the coupled branch, re-plotted separately
Example 4: three port GNR circuit

The circuit is made of two zigzag leads and one armchair lead, the right lateral one.

Scattering of mode 1 and mode 2, at energy=1.5 eV with respect to the Fermi point.
the quantum transport problem
(Schrodinger/Dirac)

the electromagnetic problem (Maxwell)

In the recent past

- The Maxwell-Schrödinger Problem in the frequency-domain
- The Maxwell-Schrödinger problem in the Time-Domain
model of the combined Dirac-Maxwell problem

3D domain \[\leftrightarrow\] Maxwell equations \[\leftrightarrow\] TLM
coupled and simultaneously solved together

2D domain \[\leftrightarrow\] Dirac/Graphene equations \[\leftrightarrow\] FDTD

1D-2D subregion (quantum device) defined inside a 3D-region
Maxwell equations

\[ \nabla \times \mathbf{E}(r, t) = -\frac{\partial \mathbf{B}(r, t)}{\partial t} \]
\[ \nabla \times \mathbf{H}(r, t) = \frac{\partial \mathbf{D}(r, t)}{\partial t} + \mathbf{J}(r, t) \]
\[ \nabla \cdot \mathbf{D}(r, t) = \rho(r, t) \]
\[ \nabla \cdot \mathbf{B}(r, t) = 0 \]

concept of the method

EM field

source terms

boundary conditions

Dirac/graphene equations

initial conditions

wave function

charge density

q |\( \psi(r, t) \)|^2

\( \nabla \times \mathbf{E}(r, t) = -\frac{\partial \mathbf{B}(r, t)}{\partial t} \)
\( \nabla \times \mathbf{H}(r, t) = \frac{\partial \mathbf{D}(r, t)}{\partial t} + \mathbf{J}(r, t) \)
\( \nabla \cdot \mathbf{D}(r, t) = \rho(r, t) \)
\( \nabla \cdot \mathbf{B}(r, t) = 0 \)
Dirac equation

- 4-components wave solution
- describes coherent carrier transport

\[
\begin{pmatrix}
V(r) + V_F \left( \begin{array}{cc}
\sigma_x (-i\hbar \partial_x + eA_x) + \sigma_z (-i\hbar \partial_z + eA_z) \\
0
\end{array} \right)
0 \\
-\sigma_x (-i\hbar \partial_x + eA_x) + \sigma_z (-i\hbar \partial_z + eA_z)
\end{pmatrix}
\psi(r; t) = \\
- \left(i\hbar \frac{\partial}{\partial t} + e\phi \right) \psi(r; t)
\]

Pauli Matrices

\[\sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \sigma_z = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}\]

\[\psi = \begin{pmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \\ \psi_4 \end{pmatrix}, \quad r = (x, z)\]

Plank’s constant

\[h = 6.626 \times 10^{-34} \text{ [J sec]} \]

\[\hbar = \frac{h}{2\pi}\]

Electron charge

\[q = -1.602 \times 10^{-19} \text{ [C]}\]
Dirac/Graphene equations

Set of 4-coupled complex hyperbolic equations

\[
i\hbar \frac{\partial \psi_1(x,z)}{\partial t} = -\{V(x,z)\psi_1(x,z)\} + v_F \left\{i\hbar \frac{\partial \psi_2(x,z)}{\partial x} + \hbar \frac{\partial \psi_2(x,z)}{\partial y}\right\} + e i\hbar \left(A_x(x,z) - iA_z(x,z)\right) \psi_2(x,z)\]

Finite-Difference schemes

- Dufort-Frankel
- Euler


Physical Properties $\rightarrow$ Computational Parameters

Electron energy

- Energy levels
- Conduction band
- Fermi level
- Band gap

- Semiconducting
  - Energy levels: $E_{\text{MIN}}$, $E_{\text{MAX}}$ (Fermi level)
  - Fermi level

- Metallic
  - Energy levels: $E_{\text{MIN}}$, $E_{\text{MAX}}$ (Fermi level)
  - Fermi level

Conduction band $\rightarrow$ Fermi level

\[
E_{\text{elec}} = \omega \hbar = hf_{\text{elec}} \Rightarrow f_{\text{elec}} = \frac{E_{\text{elec}}}{\hbar}, \quad \hbar = \frac{h}{2\pi}
\]

\[
E_{\text{MAX}} \Rightarrow f_{\text{MAX}}, \quad E_{\text{MIN}} \Rightarrow f_{\text{MIN}}
\]

\[
\lambda_{\text{MAX}} = \frac{v_F}{f_{\text{MIN}}}, \quad \lambda_{\text{MIN}} = \frac{v_F}{f_{\text{MAX}}}
\]

\[
\Delta L_{\text{grid}} \leq \frac{1}{30} \lambda_{\text{MIN}}
\]

\[
\Delta t_{\text{EM}} \leq \frac{\Delta L_{\text{grid}}}{2c}, \quad c = 3 \times 10^8 \, m/s
\]

\[
\Delta t_{\text{GNR}} \leq \frac{\Delta L_{\text{grid}}}{v_F}, \quad v_F \approx c / 300 \, m/s
\]
Propagation of a Gaussian pulse for wide-band electron energy

\[ \psi = \begin{bmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \\ \psi_4 \end{bmatrix} \begin{cases} \psi_1 = f(x, z; t) \\ \psi_2 = -i f(x, z; t) \\ \psi_3 = \psi_4 = 0 \end{cases} \]

\[ f(x, z; t) = A_N \exp\left(\frac{-(t-t_0)^2}{2\sigma_T^2}\right) \exp\left(\frac{-(x-x_0)^2}{2\sigma_x^2}\right) \exp\left(\frac{-(z-z_0)^2}{2\sigma_z^2}\right) \]

\[ \int |\psi(r, t)|^2 \, dr = 1 \Rightarrow q \int |\psi(r, t)|^2 \, dr = Q_T \]

**Computational Parameters**

- \( E_{\text{MAX}} = 1 \, \text{eV} \)
- \( f_{\text{MAX}} = 289 \, \text{THz} \)
- \( \sigma_T = 2 / f_{\text{MAX}} \)
- \( \lambda_{\text{MIN}} = 5 \, \text{nm} \Rightarrow \Delta L_{\text{grid}} = \frac{1}{32} \lambda_{\text{MIN}} = 0.12 \, \text{nm} \)
- \( \Delta t_{\text{EM}} = \frac{\Delta L_{\text{grid}}}{2c_0} = 2 \times 10^{-4} \, \text{fs} \)
- \( \Delta t_{\text{GNr}} = \frac{\Delta L_{\text{grid}}}{v_f} = 0.12 \, \text{fs} \)

A space-time pulse is injected.
Propagation of $|\psi|^2$
Propagation of $|J_z|$ and $|J_x|$.
Transmittivity of a Graphene Channel

\[ J_z(z; t) = \int_{x_1}^{x_2} J_z(x, z; t) \, dx \]

absorbing boundary conditions

\[ J_{in} \]

\[ J_{out} \]

\[ J_z(z_1, t) = u_0(t) \]

the amplitude peaks of \( H(\omega) \) are eigenenergies

\[ H_0(\omega) = \frac{J_z(z_2, \omega)}{J_z(z_1, \omega)} = \frac{F\{J_z(z_2, t)\}}{F\{J_z(z_1, t)\}} \]

Transmittivity
Transmittivity

Cut-off of the first higher mode at $E = 0.7$ eV

Increase of $v_g$ at $E = 0.1$

Fermi level

Conduction band

GNR width ~ 3 nm

$E = 0.12$ eV

$E \approx 0.75$ eV

$E = 0.12$ eV

Tight-binding (TB) method
a DFT at each point in the problem space at each of the eigenenergies $f_0$ is carried out during the simulation.
self-generated electromagnetic field in the presence of a potential barrier

\[ E_{\text{MAX}} = 1 \text{ eV} \]

\[ \Delta t_{\text{EM}} \leq \frac{\Delta L_{\text{grid}}}{2c} \]

\[ \Delta t_{\text{GNR}} \leq \frac{\Delta L_{\text{grid}}}{v_F} \]

\[ \Delta t_{\text{EM}} \leq \frac{\Delta t_{\text{GNR}}}{600} \]

\[ 5 \text{ nm} \div 6 \text{ fs} \]

EM contribution to the kinetic energy that affect:
- dynamics
- group velocity

without EM field

with EM field

\[ 6 \text{ nm} \div 6 \text{ fs} \]
wavepacket dynamics with and without the self-generated EM field

potential barrier

8 fs - EM field

4 fs – without EM field

4 fs – with EM field

8 fs – without EM field

8 fs - without EM field

4 fs - EM field

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...physically, the same effect in CNT wavepacket dynamics with and without the self-generated the EM field

$\Delta E_{\text{elec}} = 0.05 \text{ eV}$

$\Delta E_{\text{elec}} = 1 \text{ eV}$

$\Delta E_{\text{elec}} = 0.1 \text{ eV}$
comparison to experimental results: $I_{ds} - V_{ds}$

CNT FET

Infineon Technologies AG,
Corporate Research, 81730 Munich, Germany

L. Pierantoni, D. Mencarelli and T. Rozzi,
"Boundary Immittance Operator for the Combined Schrödinger-Maxwell Problem of Carrier Dynamics in Nanodevices",
work done

the combined Schrödinger/Dirac-Maxwell problem in the time-domain

dynamics of a charge wavepacket in graphene nanoribbon + EM self-generated field

...work in progress

impinging plane-wave and non-linear effects

edge and boundary conditions (carbon-metal contact)

photo-emission/generation from CNT/Graphene

unified model for electromagnetic fields and quantum transport based on the Dirac equation)
Conclusions

- The main goal of the MTT-25, Technical Committee, RF-Nanotechnology, is to provide an appropriate venue to review perspectives and foster innovation in the area of nanotechnology/nano electronics.

- MTT-25 is organizing and is involved in many worldwide activities and events, as workshops, conferences, special sessions, publications.

- The research activities of the MTT-25 members is of high relevance in the worldwide panorama.

- MTT-25 is ready to interact with the EC for focusing research platform and defining routes on Carbon-based Nanoelectronics and, in general, on the Radio-Frequency applications of nanoelectronics/nanotechnology.

- European members of MTT-25 are ready to form an enlarged network and participate to European projects.