Terahertz Emission and Detection in Double Graphene Layer Structures

Vernon E. Londagin III[1,2,3], Takayuki Watanabe[3], Tetsuya Kawasaki[3], Hiroyuki Wako[3], Stevanus Arnold[3], Stephane A. Boubanga Tombet[3], Victor Ryzhii[3], and Taiichi Otsuji[3]

[1] *Department of Physics and Engineering, University of Tulsa, Tulsa, Oklahoma, U.S.A.*
[2] *NanoJapan: International Research Experience for Undergraduates Program, Rice University, Houston, Texas, U.S.A.*
[3] *Research Institute of Electrical Communication, Tohoku University, Sendai, Miyagi, Japan*

The terahertz (THz) region of the electromagnetic spectrum, situated between electronics and photonics, has been largely unexplored until recent years. Though some devices are capable of operating in this range, there are several drawbacks that prevent them from being commercially viable. The ability to create powerful and compact devices that operate in the THz range at room temperature would be revolutionary for potential applications in homeland security, sensing, and ultra-broadband communications. Graphene, because of its many unique properties, has several advantages in the THz range. The purpose of our investigation is to utilize a gated double graphene layer structure (G-DGL) to emit and detect THz radiation using photon-assisted quantum mechanical resonant tunneling (QM-RT). We are using three different experimental setups to observe these phenomena, two for emission and one for detection. For emission, we are using a Fourier-transform far-infrared spectrometer to observe spontaneous THz emission and a THz time domain spectroscopy system to observe stimulated emission. For detection, we are using a uni-traveling-carrier photodiode (UTC-PD)-type photomixer to generate a THz continuous wave that the sample will absorb. We then measure the photo-absorption-assisted QM-RT current and look for a photo-response, indicated by the negative differential conductivity. The observation of THz detection and/or emission would be a significant leap forward in technologies that can operate effectively in the THz range and could revolutionize optoelectronic and communication technologies, as we know them today.

Terahertz Emission and Detection in Double-Graphene-Layer Structures

Vernon E. Londagin III[1,2,3], Takayuki Watanabe[3], Tetsuya Kawasaki[3], Hiroyuki Wako[3], Stevanus Arnold[3], Stephane A. Boubanga Tombet[3], Victor Ryzhii[3], and Taiichi Otsuji[3]

[1]NanoJapan Program, Rice University, Houston, Texas, U.S.A.

[2]Department of Physics and Engineering Physics, University of Tulsa, Tulsa, Oklahoma, U.S.A.

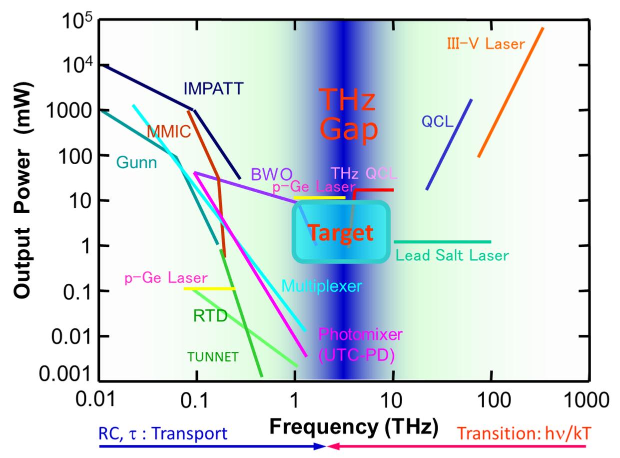
[3]Research Institute of Electrical Communication, Tohoku University, Sendai, Myagi, Japan

Contact: Vernon Londagin, vernon-londagin@utulsa.edu

Introduction

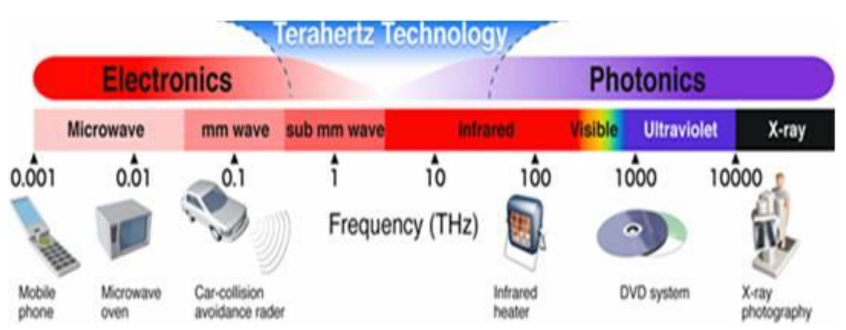
Objective

To observe the Emission and Detection of Terahertz (THz) radiation in Double Graphene Layer (DGL) based Structures.



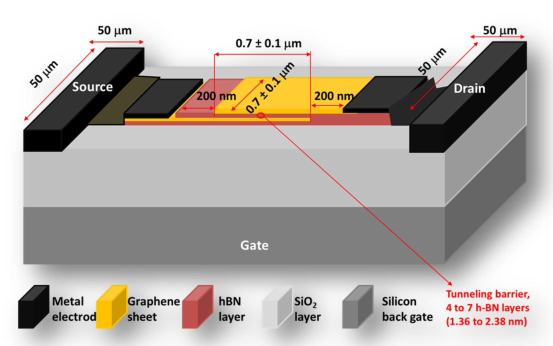
Motivation

- Conventional solid-state based devices show operational limitations in THz range.
- Revolutionary Potential Applications in homeland security, sensing, and ultra-broadband communication.



Device

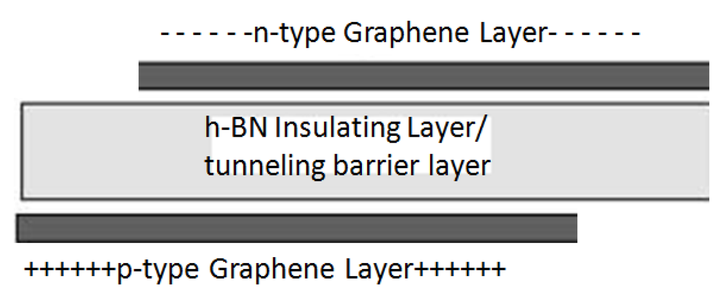
- DGL capacitor with an h-BN tunnel barrier insulation layer sandwiched between top and bottom layers of graphene.
- DGL fabricated onto a SiO2/highly-doped, low-resistive Si substrate.
- Back surface of the Si substrate is metalized to work as a gate electrode for the bottom graphene layer sheet.

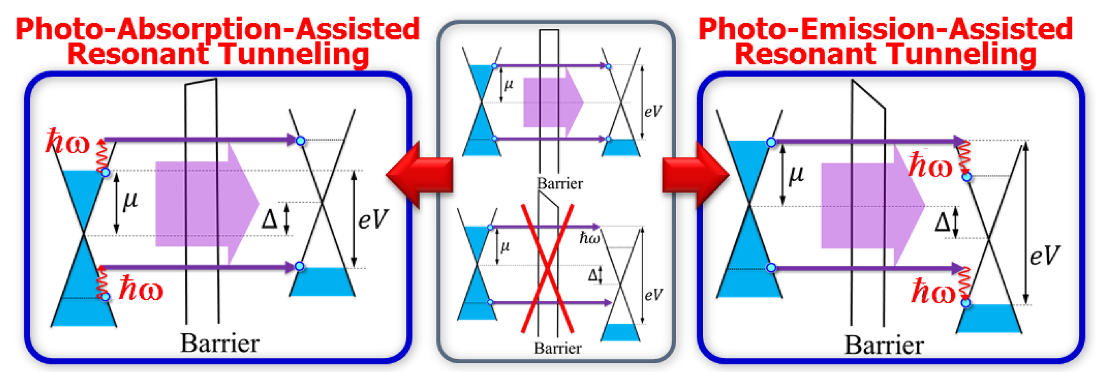


Theory: Photon Assisted Quantum Mechanical Resonant Tunneling (PA QM-RT)

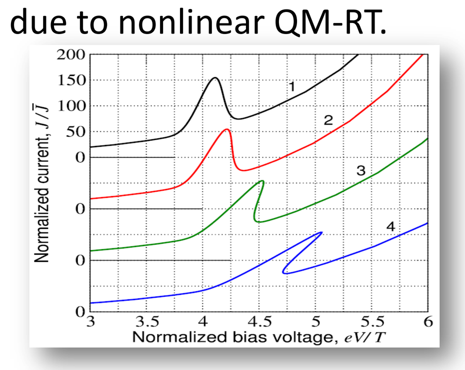
PA QM-RT

- The DC bias induces a band offset Δ of the two graphene sheets, forming the DGL capacitor.
- Pertinent gate bias is then needed to align the bands (Δ=0), QM-RT can then occur.
- In case of non-zero Δ, the QM-RT can occur by emission or absorption of the photon radiation whose photon energy is equal to Δ. This is called PA QM-RT.
- QM-RT causes all excess charges in the n-type graphene to recombine with the holes in the p-type graphene.





- I-V curves exhibit Negative Dynamic Conductivity (NDC) due to nonlinear QM-RT.



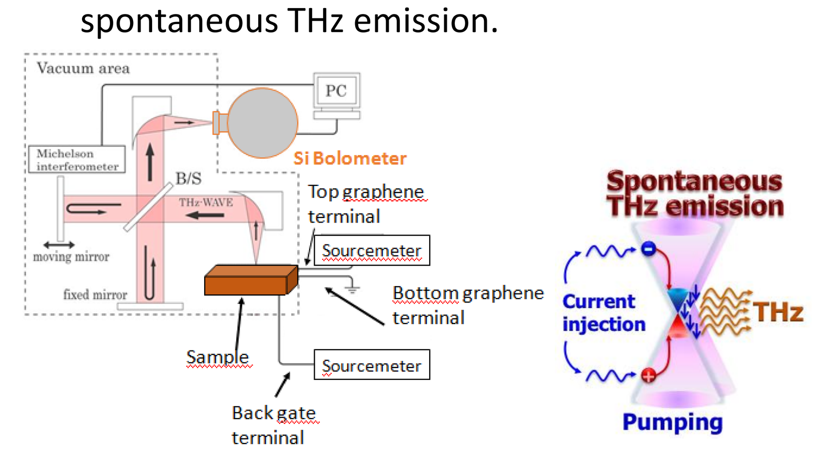
Methods: Observation of Terahertz Emission

Fourier Transform Far-Infrared Spectroscopy

FTIR setup is used to observe spontaneous THz emission from the DGL samples.

Procedure:

1. A gate bias is applied to tune the band offset to match the interacting photon energy.
2. When Δ < 0 the QM-RT will occur followed by spontaneous THz emission.

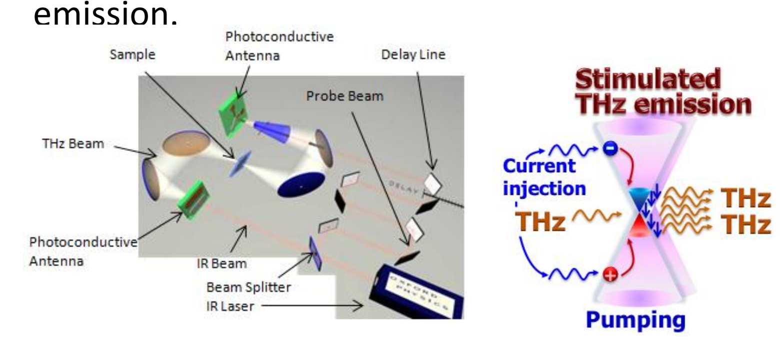


THz Time Domain Spectroscopy

Classical TDS setup is used to measure stimulated THz emission from the DGL samples.

Procedure:

1. A gate bias is applied to tune the band offset to match the interacting photon energy.
2. When Δ < 0, a THz probe pulse is used to stimulate the QM-RT via THz photon emission.

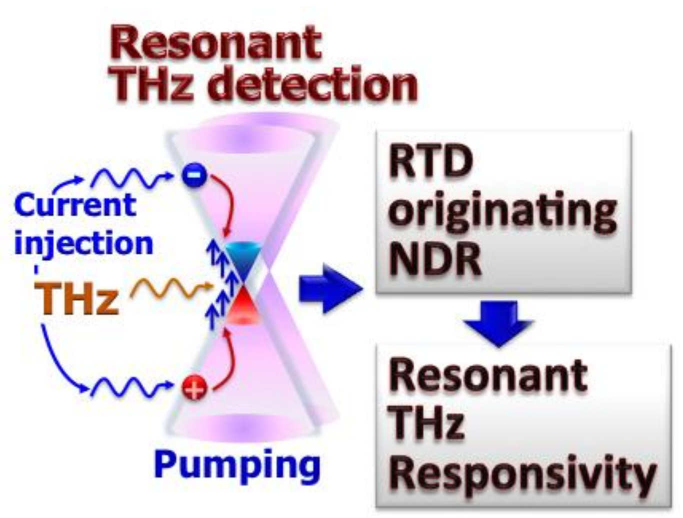


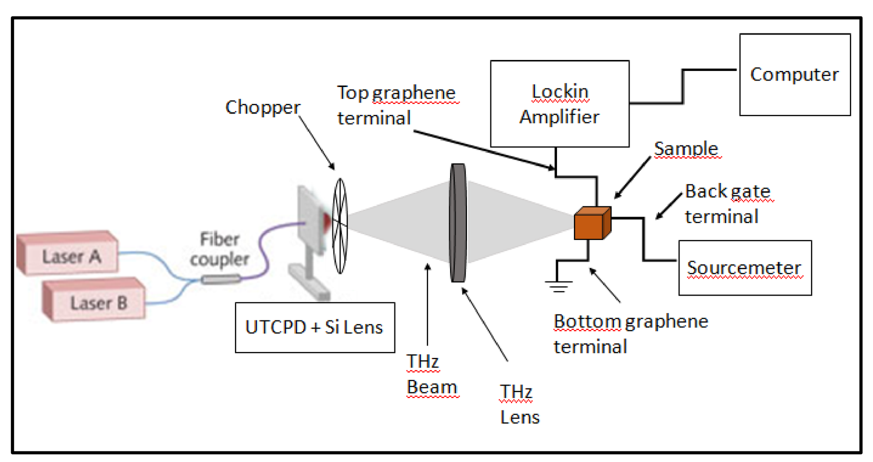
Methods: Observation of Terahertz Detection

THz Photo-Current Detection Setup

Procedure:

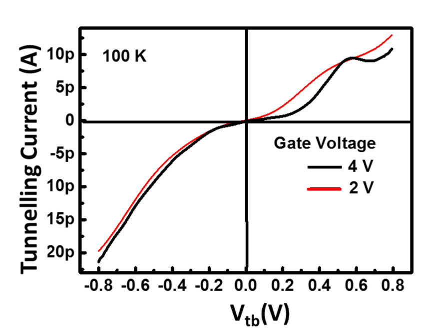
1. A gate bias is applied to tune the band offset to match the interacting photon energy.
2. When Δ > 0 the incoming CW THz beam will be absorbed by the sample, inducing the QM-RT and THz detection can be observed via photoconductive response.



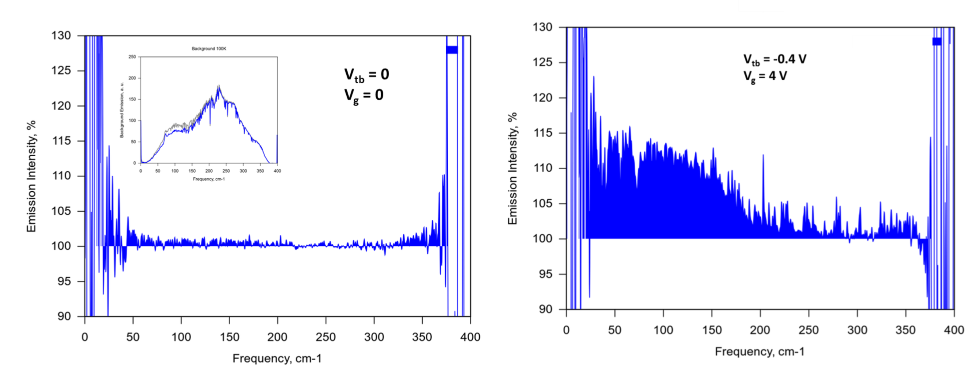


Results

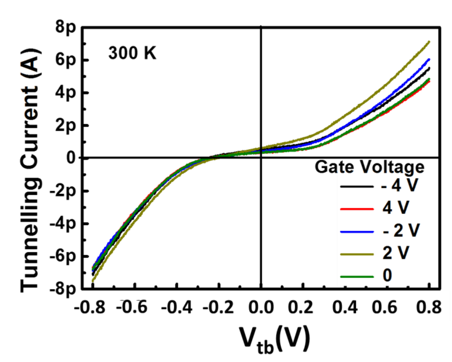
I-V Characteristics of DGL at 100 K



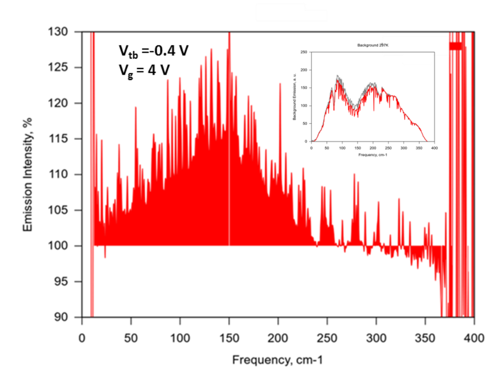
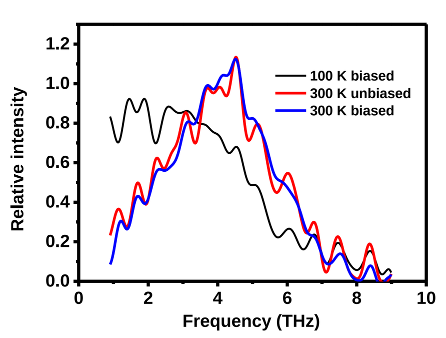
FTIR Emission Spectra of DGL at 100 K



I-V Characteristics of DGL at 300 K



FTIR Emission Spectra of DGL at 300 K

Preliminary results showing THz emission from the DGL sample.

Conclusion

- We studied Terahertz Emission and Detection in Double-Graphene-Layer Structures.
- At a low temperature (100K), we observed a NDC peak on the I-V curves due to QM-RT.
- We observed THz emission from DGL layer structures using FTIR measurements.
- The emission spectra show some dependence upon the temperature, but applied voltage dependence requires further clarification.

References:

1. L. Britnell et al., *Nature Comm.* **4**, 1794 (2013).
2. M. Ryzhii et al., *JAP* **115**, 024506 (2014).
3. V. Ryzhii et al., *APL* **104**, 163505 (2014).
4. V. Ryzhii et al, *J. Phys. D* **45**, 302001 (2012).
5. V. Ryzhii et al., *Opt. Exp.* 21, 31569 (2013).
6. V. Ryzhii et al., *APL* **103**, 163507 (2013).
7. "THz Spectroscopy and Imaging." *Delta Optics.* Irida Iberica S.L., n.d. Web. 01 Aug. 2014.

Acknowledgements: This research project was conducted as part of the 2014 NanoJapan: International Research Experience for Undergraduates Program with support from a National Science Foundation Partnerships for International Research & Education grant (NSF-PIRE OISE-0968405). For more information on NanoJapan see http://nanojapan.rice.edu. Special thanks to all those who made NanoJapan 2014 possible, and to the Gilman Foundation and Dean of the University of Tulsa's ENS Department, James Sorem, for their support