Nanoscale Optical Communications with Graphene

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***Abstract*—Graphene as a popular building block of nanotechnology having significant electronic, optical, mechanical and thermal properties has diverse growing application areas in physical, chemical, biological and technological sciences. Graphene as a tiny two-dimensional atomic layer carbon sheet is utilized in field effect transistor structures with single or multi-layer graphene sheets is promising for future nanoscale optical communication architectures because of wide range absorption from far infrared to visible spectrum, fast carrier velocity and advanced production techniques due to planar geometry. In this review, optical channels for nanoscale wireless optical communication is emphasized and literature on graphene photodetectors are summarized. The latest results on communication theoretical performance of graphene receivers are discussed by emphasizing novel nanoscale optical communication architectures. The review is concluded with the discussion of open research issues for nanoscale wireless optical communications with graphene.**

***Index Terms*—Graphene, carbon nanotube, nanoscale communications, nanoscale optical network, nanonetwork**

I. Introduction

The evolution of the society results in higher demands from technology in various applications including communications technologies. The microelectronics industry is evolving towards nanoelectronics with electronic devices of sizes below 10 nm which achieves the capability for smaller and faster components, higher memory capacity of integrated circuits (ICs), higher transmission data speed, higher bandwidth optical communication receivers etc. [1].

One of the fundamental areas for the developments in the nanoscale regime is the communications technology. The most basic functional units in nanoscale regime, i.e., *nanomachines*, can be interconnected by *nanoscale communication* channels by forming *nanonetworks* [2]. Traditional communication technologies have difficulty in nanoscale regime due to the limitations and complexities regarding size, power consumption and the quantum mechanical constraints in nanoscale regime. Various nanoscale communication alternatives can be listed as nanomechanical, acoustic, electromagnetic (and optical), chemical or molecular communication [2].

Optical wireless communications (OWC) is a complementary method to electromagnetic radio frequency (RF) communications affected significantly by nanotechnology. The nanoelectronic devices discovered along the last several decades form the foundations of the next generation optoelectronics and communication industries. Optoelectronic devices have developed significantly based on nanoscale materials such as one-dimensional (1D) nanotube and nanowire structures, two-dimensional (2D) layers of graphene and various organic/inorganic molecules [3]. Graphene and carbon nanotube have made significant advancements in nanoscale photodetector technologies.

Graphene with its groundbreaking properties has taken Nobel Prize in Physics in 2010 to Andre Geim and Konstantin Novoselov with its unique electronic and photonic properties. Graphene photodetectors (GPDs) make graphene promising for future nanoscale optical communication architectures with its ultra wide-band absorption spectrum from far-infrared (FIR) to ultra-violet (UV), fast carrier velocity, tunable absorption with graphene nanoribbon and graphene bi-layer and advantages of fabrication due to planar geometry [4], [5]. On the other hand, carbon nanotube is another promising candidate for future nanoscale communication networks. CNTs with nanometer scale diameters are ultra-light weight, strongest materials in terms of tensile strength, having extremely large thermal and ballistic conductivity of electrons at room temperature making them quasi-1D structures [6], [7]. CNT field effect transistors used as photodetectors have significant performances showing hundreds of Gb/s data rates [8]–[10].

In this article, nanoscale optical communication receivers and nanonetworks using graphene are reviewed emphasizing the communication theoretical basics, foundations for future nanoscale optical wireless communication architectures and the fundamental results, then the future works to be carried out are given. The remainder of the paper is organized as the following. In Section-II, the concept of nanoscale communications is reviewed. In Section-III, the optical communication in nanoscale regime is discussed. Then, in Section-IV, the graphene nanoscale photodetectors and optical receivers are reviewed. In Section-V, diversity combining methods for multi-receiver graphene photodetectors and parallel line-scan optical networking topology are reviewed. In VI, the performance results for graphene nanoscale optical receivers are summarized and discussed. Finally, in Section-VII, the conclusions are given summarizing the main topics and the future work for open research issues.

II. Overview of Nanoscale Communications

In 1965, nobel laureate Richard Feynman in his famous speech entitled ”There's Plenty of Room at the Bottom” pointed out miniaturization and devices in the future. Nanotechnology deals with the miniaturization and manufacturing of devices in the range of scale below 100 nanometers [2]. Nano-machines, i.e., the most basic functional units composed of a set of molecules can perform computation, sensing and actuation tasks [2]. They can interconnect and communicated to form nanonetworks enabling to share information.

Traditional communication technologies have difficulty to point out the nanoscale regime due to limitations and complexities regarding size, power consumption and the quantum

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mechanical nature of the nanoscale regime. Nanoscale communication can be achieved by nanomechanical through mechanical contacts, acoustic using ultrasonic transducers, electromagnetic through modulation of electromagnetic waves by nanoscale antennas such as graphene antennas, optical through photodetectors and light sources and chemical/molecular communication channels through message carrying molecules such as diffusion or molecular motor channels [2], [11]. Optical communications is an alternative method to molecular or other forms of communication in nanoscale. Next, optical communications in nanoscale regime is discussed.

III. Nanoscale Wireless Optical Communications

Nanoscale photodetectors have gained attention due to various advantages unique to their nanoscale nature [12]. Ultrafast, tunable and high performance graphene (2D) and carbon nanotube (1D) photodetectors have the capability to succeed hundreds of GHz bandwidths [5], [10]. Besides that, nanoscale optical antennas are discussed as a method to construct nanoscale communication units [13]. Moreover, optical nanoscale networks on chips have the ability to replace the electrical counterparts resulting in high bandwidth, low latency, scalability and low energy consumption [14]. As a result, nanoscale optical communication architectures are significantly important for next generation communication technologies.

In addition to graphene and nanotube, quantum dot infrared photodetectors (QDIPs) which are zero dimensional (OD) objects have low dark current, long excited-state lifetime, high photoconductive gain, high temperature and voltage-tunable multi-spectral operation [15], [16]. In addition to this, Quantum well infrared detectors (QWIPs) have the mature processing technology for GaAs with low cost and flexibility in high speed and multicolor applications [17].

On the other hand, Nanowire (NW) photodetectors with one dimensional (1D) structures are fabricated from metal-oxides, group II-VI, III-V, IV, VI compounds [18]. NW photodetectors are advantageous in terms of allowing dense device integration, sub-wavelength spatial resolution, enhanced light absorption in vertical arrays, high photosensitivity and gain.

Furthermore, single photon detectors makes high-sensitivity and high-resolution near-field imaging possible sensing the extremely low light powers emitted by nanoscale sources [19]. Single photon detectors can be implemented with photomultipliers, avalanche photodiodes, visible-light photon counters, superconducting nanowires, superconducting transition-edge sensors, quantum dots and semiconductor defects [20]. Next, the main focus in the article, i.e., graphene and carbon nanotube nanoscale optical communication architecture, is discussed.

IV. Graphene Nanoscale Wireless Optical Communication Receivers

Graphene with ground breaking properties has tremendous impact as a two-dimensional atomic layer carbon sheet in a hexagonal honeycomb lattice with unique electronic and photonic properties resulting in applications such as transistors, photodetectors and circuit components [4], [5]. Metal-graphene-metal (MGM) GPDs allow wide range absorption from far infrared to visible spectrum, fast carrier velocity and advanced production techniques. Graphene has high electron mobility and carrier Fermi velocity ($1/300$ of the speed of light), strong, fast and tunable broadband absorption from far infrared to visible and ultraviolet spectrum [21]–[24]. Near-ballistic electronic transport and photonic properties together with mechanical stability result in novel devices operating at room temperature [21]. Graphene is the thinnest and the strongest material having the largest surface to weight ratio where the fundamental properties of graphene and carbon nanotube compared with high performances of conventional materials are seen in Table-I.

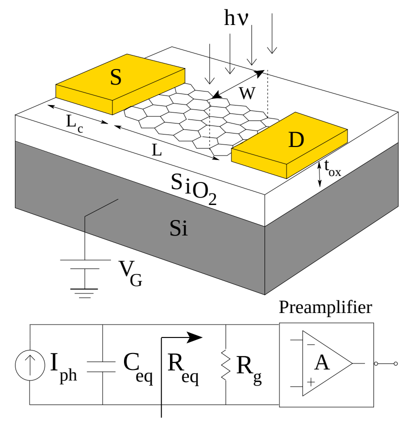
TABLE I
Graphene and CNT Properties [25]–[29]

Property	Graphene	SWNT	Other
Young's modulus	0.5-1.5 TPa	0.3-1.5 TPa	0.2 GPa strong steel
Tensile strength	1 TPa	30-200 GPa	1-2 GPa strong steel
Thermal cond. (Room Temp.)	4800-5300 W/(m.K)	6600 W/(m.K)	3300 W/(m.K) diamond
Current capacity	$> 10^8$ A/cm^2	$> 10^9$ A/cm^2	10^7 A/cm^2 Cu (d = 100 nm)
Carrier mobility (Room Temp.)	$>$ 20000 cm^2/(V s)	20000-60000 cm^2/(V s)	450-1400 cm^2/(V s) Si

Graphene photodetectors combine the wide range of optical absorption and fast carrier transport properties where metal-graphene-metal experiments show strong photocurrent response having internal quantum efficiency of 30% and hundreds of Gb/s data rate performance [5], [31], [40]. Furthermore, graphene phototransistors with p-i-n junctions have significant theoretical responsivity, i.e., $\mathcal{R}$, and dark current detectivity [32]–[34].

On the other hand, graphene suffers from low efficiency due to the low light-graphene interaction region, low absorption and the necessity to form multiple p-n junctions to sweep the charge carriers [5], [31], [35]. The efficiency can be improved with multi-layer graphene [32], increased electric field region and intensity with multiple finger devices and asymmetric metals [31].

Graphene photodetectors in the form of transistors, p-n junctions or p-i-n detectors are experimentally and theoretically analyzed in detail showing significant performances [5], [21], [31], [32], [36]–[41]. GPDs absorb light over a broad wavelength range and are ultrafast wide-spectrum photodetector devices due to its huge mobility. GPDs can have metal-graphene-metal device geometries using photo-thermoelectric effect [36], p-n junctions sweeping the photogenerated carriers by built-in electric field [5], [42], phototransistor opto-electric



(a) (b)

Fig. 1. (a) Model of metal-graphene-metal photodetector with metallic contacts and a modulating back gate [5], [31], [43], (b) equivalent circuit [5], [29], [31], [43].

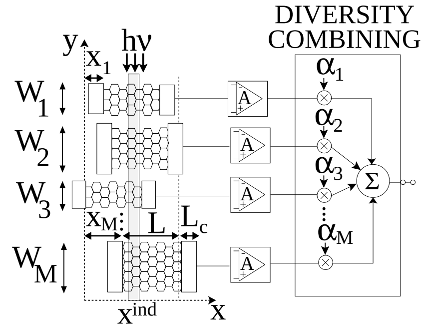


Fig. 2. Diversity combining multi-receiver graphene photodetector [29], [43].

gains [33], [34], and p-i-n geometries with multiple layers [32]. They can be either electrostatically doped by top/back gates or chemically doped by molecular dopants [5], [32], [42].

In [5], an ultrafast metal-graphene-metal photodetector is introduced for single and multi-layer graphene prepared by mechanical exfoliation of graphite and graphitic flakes deposited on Si surface covered with a 300-nm-thick SiO_2. It has symmetric S-D contact electrodes (Ti/Pd/Au) as shown in Fig. 1(a).

In [43], nanoscale single-layer symmetric metal-graphene-metal photodetectors are analyzed in terms of performance metrics for intensity modulation and direct detection non-return-to-zero on-off keying modulation showing tens of Gb/s achievable data rates with very low BERs. Furthermore, multi-receiver graphene photodetectors and parallel line-scan optical networking transmit topology are introduced increasing the efficiency of the detector. Diversity combining methods are analyzed for multi-receiver devices.

V. Parallel Line-scan Optical Nanonetworking & Diversity Combining

In [29], [43], multi-receiver graphene photodetectors, parallel line-scan optical networking transmit topology and diversity combining methods for nanoscale optical communications are, for the first time, introduced. Line-scan transmitter-receiver networking topology is proposed for broadcast covering the whole width of graphene channel in a rectangular planar receiver geometry. Furthermore, it creates distinct and controlled spatial subchannels with high resolution. It can currently be realized by systems similar to a confocal Raman microscope to form the uniform intensity line illumination pattern. Besides that, diversity combining methods are mentioned to be used on single receiver by cutting the graphene to smaller width receivers to create uniform spatial channels with improved SNR performance. More robust and efficient photodetectors performing independent of the illumination position are introduced with a diversity placement of multiple photodetectors.

A multi-receiver graphene photodetector design is shown in Fig. 2. The parallel line-scan light is incident on $0 < x^{ind} < L$, there are M receivers with widths W_i, same length L, x-axis coordinates x_i for $i \in [1, M]$ and the same orientation with respect to a reference coordinate system.

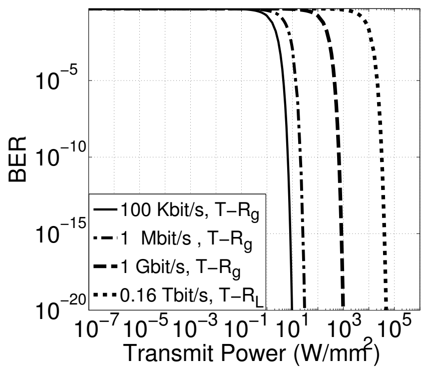
VI. Performance of Graphene Nanoscale Optical Receivers

In [29], [43], theoretical performances of graphene optical receivers and the performance increasing diversity methods are explored. It is observed that even with very low power of ≈ 1 W/mm^2, it is possible to achieve hundreds of Kb/s transmission with very low BER where the photocurrent generation region is $W_{tot} \times L/2 = 0.725\,\mu\text{m}^2$ as shown in Fig. 3. It can also succeed tens of Gb/s rate with 2 KW/mm^2 input power. Moreover, even with small area of $0.025 \times 0.775 = 0.02\,\mu\text{m}^2$, it is possible to achieve the rate of hundreds of Mb/s with 2 KW/mm^2 transmit power.

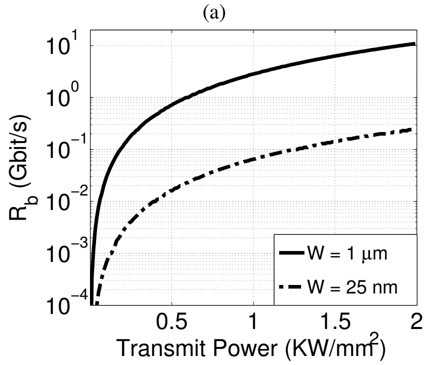
Single-layer symmetric metal-graphene-metal photodetectors are analyzed for SNR, BER and data rate performance metrics with IM/DD non-return-to-zero on-off keying optical modulation. Tens of Gbit/s data rates are achievable with very low BERs and with nanoscale size graphene photodetectors. This communication theoretical study in [29], [43] can establish the foundations of GPDs to be utilized in the future nanoscale optical communication networks.

VII. Conclusions

Graphene as a ground breaking nanoscale building block has a variety of photodetector types with significant performances. The photo-thermoelectric, symmetric metal and asymmetric metal p-n junctions, multi-layer p-i-n schemes and phototransistors are the observed major types. The basic communication theoretical performance metrics, i.e., SNR, BER and data rate, for single layer graphene and single walled carbon nanotube photodetectors are analyzed in the recent literature. Tens of Gb/s data rates for single layer graphene can be achieved with practical power levels where it is capable of THz range communication intrinsically. The novel networking concepts such as diversity combining for multi-receiver graphene photodetectors and parallel line-scan optical networking are other useful properties of graphene detectors. The fascinating performance of the graphene photodetector is



(a)



(b)

Fig. 3. BER vs. transmit power for varying R_b and thermal noise limited regions with graphene photodetector of $W_{tot} = 1\,\mu$m and (b) R_b vs. practical transmit power levels with graphene photodetectors of $W = 1\,\mu$m and 25 nm where BER is 10^{-8} [29], [43].

promising to open new optoelectonics applications in future nanoscale communication architectures.

The open research issues for graphene detectors include tuning the absorption optical spectrum by using bi-layer graphene layers, novel multi-color multi-receiver tunable structures, the communication theoretical analysis of graphene nanoribbons having band-gaps. The fascinating properties of graphene open new horizons in nanoscale science both in terms of technology and the conceptual understanding.

References

[1] J. Martinez-Duart, R. Martín-Palma, and F. Agulló-Rueda, "Nanotechnology for Microelectronics and Optoelectronics," *Great Britain: Elsevier Science*, 2006.

[2] I. Akyildiz, F. Brunetti & C. Blazquez,"Nanonetworks: A new communication paradigm", *Computer Networks*, vol. 52, pp. 2260–2279, 2008.

[3] G. Memisoglu and C. Varlikli, "Highly Efficient Organic UV Photodetectors Based on Polyfluorene and Naphthalenediimide Blends: Effect of Thermal Annealing", *International Journal of Photoenergy*, Hindawi Publishing Corporation,vol. 2012, 2012.

[4] A. Geim and K. Novoselov, "The rise of graphene," *Nat. Mater.*, vol. 6, no. 3, pp. 183–191, 2007.

[5] F. Xia, T. Mueller, Y. Lin, A. Valdes-Garcia, and P. Avouris, "Ultrafast graphene photodetector," *Nat. Nanotechnol.*, vol. 4, no. 12, pp. 839–843, 2009.

[6] A. Balandin, S. Ghosh, W. Bao, I. Calizo, D. Teweldebrhan, F. Miao, and C. Lau, "Superior thermal conductivity of single-layer graphene," *Nano Lett.*, vol. 8, no. 3, pp. 902–907, 2008.

[7] A. Jorio, G. Dresselhaus, and M. Dresselhaus, *Carbon Nanotubes: Advanced Topics in the Synthesis, Structure, Properties and Applications*. Berlin: Springer Verlag, 2008.

[8] D. Stewart and F. Leonard, "Energy conversion efficiency in nanotube optoelectronics," *Nano Lett.*, vol. 5, no. 2, pp. 219–222, 2005.

[9] D. Stewart and F. Léonard, "Photocurrents in nanotube junctions," *Phys. Rev. Lett.*, vol. 93, no. 10, p. 107401, 2004.

[10] L. Prechtel, L. Song, S. Manus, D. Schuh, W. Wegscheider, and A. Holleitner, "Time-resolved picosecond photocurrents in contacted carbon nanotubes," *Nano Lett.*, vol. 11, no. 1, pp. 269–272, 2011.

[11] B. Gulbahar, O. B. Akan, "A Communication Theoretical Modeling of Single-Walled Carbon Nanotube Optical Nanoreceivers and Broadcast Power Allocation," *IEEE Transactions on Nanotechnology*, vol.11, no.3, pp. 395-405, March 2012.

[12] R. Ramesh, M. Madheswaran, and K. Kannan, "Physical noise model of a uniformly doped nanoscale FinFET photodetector," *Optik-International Journal for Light and Electron Optics*, 2011.

[13] I. Akyildiz and J. Jornet, "Electromagnetic wireless nanosensor networks," *Nano Communication Networks*, vol. 1, no. 1, pp. 3–19, 2010.

[14] H. Gu, J. Xu, and Z. Wang, "A novel optical mesh network-on-chip for gigascale systems-on-chip," in *Proc. IEEE Asia Pacific Conf. on Circuits and Systems (APCCAS)*, Macao, November 2008, pp. 1728–1731.

[15] K. Sattler, *Handbook of Nanophysics: Functional Nanomaterials*, vol. 5. FL, USA: CRC Pr., 2010.

[16] L. Lin, C. Wang, M. Hegg, and L. Huang, "Quantum dot nanophotonics-from waveguiding to integration," *Journal of Nanophotonics*, vol. 3, no. 1, p. 031603, 2009.

[17] H. Schneider and H. Liu, *Quantum Well Infrared Photodetectors: Physics and Applications*. Berlin: Springer, 2007.

[18] C. Soci, A. Zhang, X. Bao, H. Kim, Y. Lo, and D. Wang, "Nanowire photodetectors," *Journal of Nanoscience and Nanotechnology*, vol. 10, no. 3, pp. 1430–1449, 2010.

[19] D. Bitauld, F. Marsili, A. Gaggero, F. Mattioli, R. Leoni, S. Nejad, F. Levy, and A. Fiore, "Nanoscale optical detector with single-photon and multiphoton sensitivity," *Nano Lett.*, vol. 10, no. 8, pp. 2977–2981, 2010.

[20] R. Hadfield, "Single-photon detectors for optical quantum information applications," *Nat. Photonics*, vol. 3, no. 12, pp. 696–705, 2009.

[21] F. Bonaccorso, Z. Sun, T. Hasan, and A. Ferrari, "Graphene photonics and optoelectronics," *Nat. Photonics*, vol. 4, no. 9, pp. 611–622, 2010.

[22] Z. Sun, T. Hasan, F. Torrisi, D. Popa, G. Privitera, F. Wang, F. Bonaccorso, D. Basko, and A. Ferrari, "Graphene mode-locked ultrafast laser," *ACS Nano*, vol. 4, no. 2, pp. 803–810, 2010.

[23] A. Wright, J. Cao, and C. Zhang, "Enhanced optical conductivity of bilayer graphene nanoribbons in the terahertz regime," *Phys. Rev. Lett.*, vol. 103, no. 20, p. 207401, 2009.

[24] J. Dawlaty, S. Shivaraman, J. Strait, P. George, M. Chandrashekhar, F. Rana, M. Spencer, D. Veksler, and Y. Chen, "Measurement of the optical absorption spectra of epitaxial graphene from terahertz to visible," *Appl. Phys. Lett.*, vol. 93, no. 13, p. 131905, 2008.

[25] P. Avouris and R. Martel, "Progress in carbon nanotube electronics and photonics," *MRS Bulletin*, vol. 35, no. 04, pp. 306–313, 2010.

[26] A. Nasibulin and S. Shandakov, "Aerosol synthesis of single-walled carbon nanotubes," *Aerosols: Science and Technology*, vol. 3, p. 1, 2011.

[27] L. Liao, Y. Lin, M. Bao, R. Cheng, J. Bai, Y. Liu, Y. Qu, K. Wang, Y. Huang, and X. Duan, "High-speed graphene transistors with a self-aligned nanowire gate," *Nature*, vol. 467, no. 7313, pp. 305–308, 2010.

[28] C. Chen, M. Aykol, C. Chang, A. Levi, and S. Cronin, "Graphene-silicon schottky diodes," *Nano Letters*, vol. 11, pp. 1863–1867, 2011.

[29] B. Gulbahar, "Nanoscale Wireless Optical Communication Receivers with Graphene and Carbon Nanotube," *Ph.D. dissertation*, Dept. of Electrical & Electronics Engineering, Koc University, Istanbul, Turkey, 2012.

[30] J. Park, Y. Ahn, and C. Ruiz-Vargas, "Imaging of photocurrent generation and collection in single-layer graphene," *Nano Lett.*, vol. 9, no. 5, pp. 1742–1746, 2009.

[31] T. Mueller, F. Xia, and P. Avouris, "Graphene photodetectors for high-speed optical communications," *Nat. Photonics*, vol. 4, no. 5, pp. 297–301, 2010.

[32] V. Ryzhii, M. Ryzhii, N. Ryabova, V. Mitin, and T. Otsuji, "Terahertz and infrared detectors based on graphene structures," *Infrared Phys. Technol.*, vol. 54, no. 3, pp. 302–305, 2011.

[33] V. Ryzhii and M. Ryzhii, "Graphene bilayer field-effect phototransistor for terahertz and infrared detection," *Phys. Rev. B*, vol. 79, no. 24, p. 245311, 2009.

[34] V. Ryzhii, V. Mitin, M. Ryzhii, N. Ryabova, and T. Otsuji, "Device model for graphene nanoribbon phototransistor," *Appl. Phys. Expr.*, vol. 1, no. 6, p. 3002, 2008.

[35] T. Echtermeyer, L. Britnell, P. Jasnos, A. Lombardo, R. Gorbachev, A. Grigorenko, A. Geim, A. Ferrari, and K. Novoselov, "Strong plasmonic enhancement of photovoltage in graphene," *Nat. Commun*, vol. 2, p. 458, 2011.

[36] X. Xu, N. Gabor, J. Alden, A. van der Zande, and P. McEuen, "Photo-thermoelectric effect at a graphene interface junction," *Nano Lett.*, vol. 10, no. 2, pp. 562–566, 2009.

[37] M. Lemme, F. Koppens, A. Falk, M. Rudner, H. Park, L. Levitov, and C. Marcus, "Local on-off control of a graphene p-n photodetector," *Arxiv preprint arXiv:1012.4745*, 2010.

[38] K. Lai, C. Fung, H. Chen, R. Yang, B. Song, and N. Xi, "Fabrication of graphene devices for infrared detection," in *Proc. IEEE Nanotechnology Materials and Devices Conf. (NMDC)*, Monterey, CA, October 2010, pp. 14–17.

[39] T. Mueller, F. Xia, M. Freitag, J. Tsang, and P. Avouris, "Role of contacts in graphene transistors: A scanning photocurrent study," *Phys. Rev. B*, vol. 79, no. 24, p. 245430, 2009.

[40] J. Park, Y. Ahn, and C. Ruiz-Vargas, "Imaging of photocurrent generation and collection in single-layer graphene," *Nano Lett.*, vol. 9, no. 5, pp. 1742–1746, 2009.

[41] R. Olac-vaw, H. Kang, T. Komori, T. Watanabe, H. Karasawa, Y. Miyamoto, H. Handa, H. Fukidome, T. Suemitsu, M. Suemitsu, *et al.*, "Optoelectronic application of multi-layer epitaxial graphene on a Si substrate," in *Proc. IEEE 3rd Int. Nanoelectronics Conf. (INEC)*, Hong Kong, China, January 2010, pp. 224–225.

[42] F. Xia, T. Mueller, R. Golizadeh-Mojarad, M. Freitag, Y. Lin, J. Tsang, V. Perebeinos, and P. Avouris, "Photocurrent imaging and efficient photon detection in a graphene transistor," *Nano Lett.*, vol. 9, no. 3, pp. 1039–1044, 2009.

[43] B. Gulbahar, O. B. Akan, "A Communication Theoretical Modeling of Single-layer Graphene Photodetectors and Efficient Multi-receiver Diversity Combining," *IEEE Transactions on Nanotechnology*, vol.11, no.3, pp. 601 - 610, May 2012.