Graphene-gated GaAs OPFET photodetector and oscillator for 5G applications

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Abstract: With the advancement of technology, the RF communication bandwidth is switching towards 5G and 6G communications. To relieve the congestion of traffic imposed on RF communication, operating in the optical domain or integrating RF and optical communication is imperative. The core components in this scenario are the oscillators as transmitters and photodetectors as receivers. These devices should be capable of high-speed and high-gain operation simultaneously. In this paper, the potential of graphene-gated GaAs front-illuminated OPFET (Optical Field Effect Transistor) as oscillator and detector towards 5G applications is explored. The OPFET device exhibits an oscillation frequency of 1.63 GHz to 1.8 GHz, tuned with optical illumination. The gain can be varied between 3.94 dB to 4.5 dB at the oscillation frequency. Under photodetection mode of operation, the device exhibits a maximum 3-dB bandwidth of 2.234 GHz, an $f_T$ of 5.33 GHz at the bandwidth frequency, and a responsivity of $3.3 \times 10^6$ A/W at a photon flux density of $10^{19}$ m$^{-2}$s$^{-1}$. A drain bias voltage of 3.94 V and a gate bias voltage of 0 V are applied in both cases. The device responses are contrasted with that of the Au (gold) gated OPFET. The explored devices have great potential for sub-6 GHz 5G applications.

Keywords: Graphene, GaAs, Au, OPFET, photodetector, oscillator, 5G, harsh.

1. INTRODUCTION

Communications based on 5G and 6G technologies cater to mobile and other related telecommunications. The 5G frequencies include (450 MHz to 6 GHz), (24.250 GHz to 52.600 GHz), (5925 to 7150 MHz), (64 GHz to 86 GHz), and also unlicensed spectrum [1]. 6G and higher variants may employ the 95 GHz to 3 THz bands [2]. The advantages of these technologies are high capacity, security, connectivity, and quality links, as well as low latency and low power consumption networks [3]-[5]. But, RF-based communications suffer from regulatory spectrum use, restricted spectrum band, and interference with nearby RF access points [6]. These issues can be resolved by optoelectronic integration with RF electronics or using the optical domain alone. Optical communication can be categorised into wireless or wired communication. Wired communication uses high-speed fibre-based optical links [7], whereas free-space optical communication (FSOC), visible light communication (VLC), light detection and ranging (LiDAR), Light-Fidelity (Li-Fi), and optical camera communication (OCC) are different forms of wireless communication [6].

The core elements of any communication system are the signal sources and the detectors. When operating in the optical domain, these are optoelectronic oscillators and photodetectors, respectively. To suit 5G applications, high-speed and high-gain source/detector characteristics are expected. One
potential candidate inherently possessing these characteristics is the optically-controlled MESFET (Metal-Semiconductor Field Effect Transistor) or OPFET (Optical Field Effect Transistor). This device has been thoroughly investigated across the past few decades towards these applications [8]-[22]. But, none of them explores the detector characteristics of graphene-gated conventional front-illuminated GaAs OPFET and its potential for possible use as an optoelectronic oscillator for 5G applications. In this work, these aspects have been suitably investigated and analysed. To the best of the authors’ knowledge, the present investigation employs an S-parameter characterisation approach to the OPFET device for the first time to analyse the stability condition of the device as an oscillator and to determine the oscillation frequency.

Graphene is an emerging 2-D material with outstanding properties such as high optical transmittance, high mechanical flexibility, high robustness, bias-dependent tunable work function, ultra-high carrier mobility, light weight, high saturation velocity, zero effective mass of carriers, excellent chemical/physical stability etc. Because of the absence in bandgap in monolayer graphene under zero bias conditions, it is considered a semi-metal. It forms an excellent transparent electrode apart from its outstanding resilience to adverse environments such as high temperatures. GaAs is a semiconductor with moderate bandgap, high saturation velocity, high mobility, moderate to high optical absorption coefficients, and short minority carrier lifetime. It also has the potential to withstand certain high temperatures [23]. Thus, the combination of graphene and GaAs as electrode-semiconductor materials certainly have the edge over other commonly used materials under hostile environments like elevated temperatures. These environments are typical of automotive, space, and aeronautics 5G applications.

The rest of the paper includes the following: OPFET model, results and discussion, followed by the conclusion.

2. OPFET MODEL

The conventional front-illuminated OPFET is represented in figure 1 [10]. In figure 1, ‘M’ denotes the metal contact and ‘SI’ means semi-insulating. The active layer and the substrate regions are considered to be n-type and p-type moderately, uniformly doped, respectively. The substrate is rendered slightly p-type semi-insulating by doping with deep level impurity, Cr (chromium). The transparent gate of the device allows the radiation to get absorbed in the channel and substrate regions, creating electron-hole pairs. The holes traverse towards the junctions, whereas the electrons move towards the channel. The electrons constitute a drain-to-source current upon the application of drain-to-source voltage by drifting across the two electrodes, thus, increasing the channel’s conductivity (photoconductive effect). The holes induce a photovoltage across the gate junction upon crossing the junction, which reduces the depletion width and enhances the drain-to-source current (external photovoltaic effect). The photovoltaic effect resulting from induced photovoltage at the active layer-substrate junction will not affect the channel width. This is ascribed to the moderately doped channel and semi-insulating substrate, which cause zero channel depletion and total substrate depletion.

2.1. Device modelling

The electron and hole continuity equations have been solved analytically in the various regions [12]. The solutions are provided below:

2.1.1. Photogenerated hole density in the gate-junction region

\[
p(y) = A_I + \alpha \Phi \tau_{sp} B_i \left[ 1 - \frac{1}{(1 - \alpha v_f \tau_{sp})} \right] \exp \left( -\frac{y}{v_f \tau_{sp}} \right),
\]

\[
A_I = \frac{\alpha \Phi \tau_{sp} \exp(-\alpha y)}{(1 - \alpha v_f \tau_{sp})}, \quad B_i = \exp \left[ -\left( \alpha - \frac{1}{v_f \tau_{sp}} \right) y_d \right].
\]
In equation (1), $\Phi$ is the photon flux density, $v_y$ is the saturated hole velocity, $\alpha$ is the semiconductor absorption coefficient, $y_{dg}$ is the gate junction extension of the depletion region measured from the surface, $\tau_{ac}$ is the hole lifetime under ac condition, and $y$ is the distance from the surface towards the substrate. Drift and recombination phenomena occur in this region.

In equation (1), the term $(1-\alpha v_y \tau_{ac})$ is to be treated as it is if $(\alpha v_y \tau_{ac}) < 1$ and is to be replaced with a maximum value closer to 1 when it exceeds or equals 1.

![Fig 1. The sketch of the front-illuminated OPFET [10].](image)

### 2.1.2. Electron density in the channel region

$$n(y) = \alpha \Phi \tau_{ac} A_2 \exp \left( \frac{-y}{L_{ao}} \right) - B_2,$$

where $A_2 = \left[ 1 + \frac{1}{(\alpha^2 L_{ao}^2 - 1)} \right]$ and $B_2 = \frac{\alpha \Phi \tau_{ac} \exp(-\alpha y)}{(\alpha^2 L_{ao}^2 - 1)}$.

$L_{ao}$ is the ac diffusion length of electrons, given by $L_{ao} = (D_e \tau_{ac})^{1/2}$, $D_e$ is the diffusion coefficient for electrons, and $\tau_{ac}$ is the electron lifetime under ac condition. The carrier transport in this region is governed by diffusion and recombination.

### 2.1.3. Electron density in the depletion region

$$n(y) = \frac{\alpha \Phi \tau_{ac} \exp(-\alpha y)}{(1 + \alpha \nu y_{s1} \tau_{ac})},$$

where $\nu y_{s1}$ is the electron saturated velocity. Drift and recombination are the transport phenomena in this region.

In equation (3), the factors in the denominator are to be treated similarly as above.

The individual contributions from the doping induced charge under illumination, the photo-induced electron charge from the channel, and the gate and substrate depletion regions constitute the total drain-to-source current.

### 2.1.4. Drain current

The drain current is computed by [24]:

$$I_d = I_{ds} \tanh (\eta V_{DS}) + V_{ds} / R_{sh},$$

where $V_{DS}$ is the applied drain voltage, $\eta$ is the ratio of drain-to-source conductance computed at $V_{DS}=0$. 

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to the saturation current, $I_{dss}$ is the drain-to-source saturation current, and $R_{sh}$ is the drain-to-source shunt resistance. Refer to [25] for the modelling of series resistances.

2.1.5. Oscillator Design

The equivalent circuit of common source OPFET is depicted in figure 2, where the symbols being represented have their usual meaning.

From the equivalent circuit, the Y-parameters of the device have been obtained [26]. The Y-parameters are converted to S-parameters under suitable source/load impedances [27]. One important factor which is necessary but not sufficient for oscillation is the Rollett’s stability factor ($K$-factor). It should be less than unity. It is given by [28]:

$$K = \frac{1 - |S_{11}| - |S_{21}| + |\Delta|^2}{2|S_{12}| |S_{21}|},$$

(5)

where $\Delta = S_{11}S_{22} - S_{12}S_{21}$. The oscillation frequency and the combination of source/load impedances that will produce stable oscillation are determined by the S-parameter characterisation approach. In this approach, the device will produce stable oscillations if the following condition is satisfied [28]:

$$|\Gamma_s||S_{11}| = 1,$$

(6)

where $S_{11} = S_{11} + \frac{S_{12}S_{21}\Gamma_{L}}{1 - S_{12}\Gamma_{L}}$ and $\Gamma_s = \frac{Z_s - Z_0}{Z_s + Z_0}$ (reflection coefficient of the source), $\Gamma_L = \frac{Z_L - Z_0}{Z_L + Z_0}$ (reflection coefficient of the load), $Z_s$ and $Z_L$ are the source and load impedances, respectively, $Z_0$ is the characteristic impedance of 50 ohms. If the condition given by equation (6) is satisfied implies that its dual condition at the other port is also satisfied:

$$|\Gamma_L||S_{22}| = 1.$$

(7)

The frequency at which the oscillations conditions are satisfied is the resonance or the oscillation frequency, and the source/load impedances are the resonance or tuned circuits.

3. RESULTS AND DISCUSSION

The simulation program has been run in MATLAB software. The device is studied at an operating wavelength of 600 nm. The drain bias is varied between 1.3 V to 25 V. The gate bias is set to 0 V. The photon flux densities used ($10^{16}$, $10^{19}$, and $10^{22}$ /m$^2$-s) correspond to power densities of 0.33 μW/cm$^2$, 0.33 mW/cm$^2$, and 0.33 W/cm$^2$, respectively. The device dimensions are suitably chosen from scaling rules [29]: 4 μm gate length, 150 μm gate width, 0.3 μm active layer thickness, and
doping concentration of $4 \times 10^{22} / \text{m}^3$. The surface to substrate thickness is 1 μm [13]. The parameters utilised for calculation are provided in table 1. Table 2 presents the estimated performance metrics of the graphene-gated GaAs OPFET photodetector at a drain-to-source bias of 3.94 V.

Table 1. Parameters used in the calculation.

| Symbol | Parameter                                      | Value                        | Ref. | Unit |
|--------|-----------------------------------------------|------------------------------|------|------|
| $\Phi_B$ | Schottky Barrier Height (Au/graphene-GaAs) | (0.865/0.795)               | [30]. | (eV) |
| $\mu$ | Low field electron mobility                   | (0.52)                       | [32] | (m$^2$/V.s) |
| $v_{y1}$ | Saturated electron velocity                   | $\sim 1.2 \times 10^5$      | [13] | (m/s) |
| $v_y$ | Saturated hole velocity in the $y$-direction | $\sim 0.9 \times 10^5$      |      | (m/s) |
| $\tau_p$ | Lifetime of holes                             | $10^{-8}$                    | [13] | (s)  |
| $\tau_n$ | Lifetime of electrons                         | $10^{-6}$                    | [13] | (s)  |
| $\varepsilon$ | Permittivity                                  | $1.14 \times 10^{-10}$      | [32] | (F/m) |
| $\alpha$ | Absorption Coefficient                        | $4 \times 10^6$             | [33] | (/m) |

Table 2. Characteristics of Graphene-GaAs front-illuminated OPFET

| Photon Flux Density ($/\text{m}^2 \cdot \text{s}$) | DC Responsivity (A/W) | 3-dB Bandwidth (Hz) | DC Transconductance (S) | DC Gate to Source Capacitance (F) | Unity-gain cut-off frequency (Hz) @ DC/BW freq |
|-------------------------------------------------|-----------------------|----------------------|------------------------|----------------------------------|----------------------------------|
| $10^{16}$                                      | 2.29 $\times 10^7$    | 1 GHz                | 12.3 mS                | 0.367 pF                         | 5.33/5.5 GHz                     |
| $10^{19}$                                      | 3.3 $\times 10^6$     | 2.234 GHz            | 14.3 mS                | 0.51 pF                          | 4.46/5.33 GHz                    |
| $10^{22}$                                      | 1.37 $\times 10^6$    | 1.48 MHz             | 21.3 mS                | 0.28 pF                          | 9.42/8.25 GHz                    |

The graphene-gated GaAs front-illuminated OPFET under investigation exhibits photovoltages of (0.45 V, 0.63 V, and 0.81 V) at the corresponding flux densities of ($10^{16}$, $10^{19}$, and $10^{22}$/m$^2$-s) as opposed to (0.52 V, 0.7 V, and 0.88 V) in the Au-gated device studied in previous work [34]. The high photovoltages arise from the extra amplification factor of ($\alpha v_y \tau_{op}$) in the equation for hole density (1) over the primary hole density and the decreasing denominator term ($1-\alpha v_y \tau_{op}$) by one order magnitude. Additionally, since the device is illuminated from the surface side, at the optical wavelength of 600 nm, the moderate absorption coefficient of $4 \times 10^6 /\text{m}$ corresponding to an absorption depth of 0.25 μm is sufficient enough to create a significant number of photocarriers in the gate depletion region. The contrasting photovoltages in the graphene- and Au-gated devices are attributed to the higher barrier height in the Au-gated device (0.865 eV) as opposed to graphene-gated OPFET (0.795 eV). This higher barrier height decreases the reverse saturation current density across the Schottky junction, thus, boosting the photovoltage. Due to the high photovoltages in both cases, large photovoltaic currents are generated. The dark current is higher in the graphene-gated device (12 mA) in contrast with Au-gated OPFET (11.3 mA) due to larger depletion width in the Au-gated device arising from the higher barrier height with analogous series resistances in both cases. The drain currents under illumination are equal in both cases (16.7 mA, 18.8 mA, and 39.9 mA). It is known from [14] that when the barrier height apparent to the carriers is lower, the sensitivity of the depletion width to applied photovoltage is more than compared to the higher barrier height device. In the present case, since the device with graphene gate possesses a lower barrier height with a larger dark current, whereas the photovoltages are higher in the Au-gated device, the compensation mechanisms induced by these opposite effects result in equal currents. However, the photocurrents generated by the Au-gated device are higher due to the lower dark current. These larger photocurrents produce wider 3-dB bandwidths in the Au-gated device (1.62 GHz and 3.1 GHz) as compared to (1 GHz and 2.23 GHz) in the graphene-gated device at the lower intensities. At the higher intensity, the photoconductive effects from the gate junction region, the neutral channel region, and the substrate depletion region also contribute significantly with almost equal contributions in both cases. The equal
contributions emanate from the compensation mechanism discussed earlier, which maintains equal depletion widths in both cases, thus, extracting similar photoconductive charges. The minority hole carrier lifetime being of the order of nanoseconds produces 3-dB bandwidths in the GHz range under photovoltaic conditions. The photoconductive lifetime being of the order of microseconds results in MHz range bandwidths (1.6 MHz in the Au-gated device and 1.477 MHz in the graphene-gated OPFET) at the higher intensity. The higher photocurrents also produce higher responsivities in the Au-gated OPFET ($2.6 \times 10^9$ A/W, $3.7 \times 10^6$ A/W, and $1.39 \times 10^4$ A/W).

The dc transconductances and gate-to-source capacitances exhibit almost equal values in both the graphene-gated and Au-gated devices. The equal values arise from the compensation phenomena stated earlier. The transconductances increase with optical power (figure 2) due to the increase in photovoltages and the additional contribution from the photoconductivity at the higher intensity. The capacitances show a similar behaviour except at the higher intensity due to the effective de-ionization of the space charge ions by the photogenerated electrons in the junction region since the photogenerated electron density is comparable to the depletion charge density at this power level (figure 3). The moderately high transconductances and moderate capacitances result in moderate unity-gain cut-off frequencies in both cases.

The oscillation performance of the graphene-gated OPFET is shown in table 3 at a drain-to-source bias of 3.94 V after the stability factor ($K$-factor) for oscillation and other oscillation conditions at the ports have been satisfied. The Au-gated device also shows the same performance since the oscillation parameters are dependent upon the transconductance, gate-to-source, gate-to-drain, and drain-to-source capacitances, the drain-to-source resistance, and the drain-to-source saturation current, which are estimated to be equal in both the devices. This is attributed to the reasons

| Photon Flux Density ($/m^2s$) | Source Impedance (ohms) | Load Impedance (ohms) | Oscillation Frequency (Hz) | Gain ($S_{21}$ dB) | Phase ($S_{21}$ degrees) |
|-------------------------------|-------------------------|-----------------------|---------------------------|-------------------|-------------------------|
| $10^{16}$                     | 270 $\Omega/8$ nH      | 27 $\Omega/17$ nH    | (1.47, 1.63, 1.8 GHz)     | 4.1 dB            | 144.3°                  |
| $10^{19}$                     | 270 $\Omega/8$ nH      | 27 $\Omega/17$ nH    | 1.63 GHz                  | 4.5 dB            | 137.12°                 |
| $10^{22}$                     | 270 $\Omega/8$ nH      | 27 $\Omega/17$ nH    | 1.8 GHz                   | 3.94 dB           | 115.95°                 |
discussed above. The device exhibits resonance at a source resistance of 270 Ω, source inductance of 8 nH, load resistance of 27 Ω, and load inductance of 17 nH. At the flux density of $10^{16}$ /m$^2$-s, the OPFET device resonates over a narrow band of frequencies ranging from 1.47 GHz to 1.8 GHz. This is possible when the oscillation conditions are satisfied at a band of frequencies instead of a single frequency. This can be improved by optimisation. As the flux density increases to $10^{19}$ /m$^2$-s, the oscillation frequency reduces to 1.63 GHz with respect to the highest frequency (1.8 GHz) at the previous flux density. This observation is in line with previous studies [19]-[21]. Since the oscillation frequency is dependent only upon the intrinsic capacitances and is independent of the transconductance and the intrinsic resistances [20], the increase in optical power boosts the capacitances (figure 3 and figure 4) and reduces the resonant frequency. At the higher flux density of $10^{22}$ /m$^2$-s, there is an increase in the oscillation frequency to 1.8 GHz. Although the dc gate-to-source capacitance undergoes a fall in its value, at the frequency of oscillation, the capacitance increases (figure 3). This is ascribed to the significant reduction in the de-ionization process at high frequencies due to the modulation of electron lifetime with frequency. Additionally, the high photovoltage, although modulated with frequency, is sufficient enough to open many of the depleted regions, thus registering sensitivity. Also, there is a significant boost in the gate-to-drain capacitance at the higher intensity (figure 4). Even though the capacitances increase, the oscillation frequency increases. The reason behind this is still being investigated by the authors.

![Figure 4](image_url)

**Fig 4.** Gate-to-drain capacitance as a function of modulation frequency at various photon flux densities.

![Figure 5](image_url)

**Fig 5.** Polar plots of $S_{21}$ at different flux densities.

The oscillator gain initially increases from 4.1 dB to 4.5 dB as the flux density is varied from $10^{16}$ to $10^{19}$ /m$^2$-s and then reduces to 3.94 dB at the flux density of $10^{22}$ /m$^2$-s. The gain, which is directly proportional to transconductance and inversely related to capacitance, exhibits an initial increase due to the significant boost of the transconductance with optical power while the capacitance increases at a slower rate (compare figure 2, 3 and 4). At the higher flux density, the gain falls since the transconductance increases at a slower rate than the capacitances at the oscillation frequency. The significant boost of capacitances is due to the reasons stated earlier. It is further observed that the oscillator phase reduces when the optical power increases. Thus, the oscillation frequency, gain, and phase can be suitably tuned with optical power. Figure 5 presents the simulated polar plots of the device at different radiation flux densities indicating that the gain and phase of the FET can be controlled to a larger extent when the optical power increases. This can have a significant bearing on the oscillator design when performing optimisation. The performance metrics estimated here are in line or close to the basic industrial standards for IoT (Internet of Things), i.e. IEEE802.15.4 based on
Zigbee Technology operating in there frequency bands (868MHz in Europe, 915MHz in the USA, and 2.4 GHz globally) [35], [36]. These standards are further divided into standards such as WirelessHART (2007) and ISA100.11a (2009) for employment in ultra-high reliability and ultra-low power industrial harsh environments. The performance also suits for two of the three frequency bands (183–683 MHz, 1640–2140 MHz, and 2200–2700 MHz) studied in [37] for indoor industrial applications. Further optimisation of the investigated devices will ensure complete compatibility with these standards.

4. CONCLUSION

The detector and oscillator characteristics of the graphene-gated GaAs front-illuminated OPFET towards optically-driven 5G applications were simulated. The performance was compared to that with the Au-gated device studied in previous work. The graphene-gated OPFET delivered the same amplification and oscillation performance as that with the Au-gated device, whereas it showed inferior response with respect to 3-dB detection bandwidth and the responsivity. The results were analysed with respect to the photovoltaic and the photoconductive effects. The device exhibits a maximum oscillation frequency of 1.8 GHz and a minimum of 1.63 GHz, tuned with optical illumination. The gain can be varied between 3.94 dB to 4.5 dB, and the phase can be tuned between 115.95° to 144.3° with a change in the flux density. The device operated as a detector shows a maximum 3-dB bandwidth of 2.234 GHz, a dc responsivity of $3.3 \times 10^6$ A/W, and an $f_T$ of 5.33 GHz at the bandwidth frequency at a flux density of $10^{19}$/m²-s at a drain-to-source bias of 3.94 V and a gate bias of 0 V. These performance metrics, together with the ability of the graphene and GaAs materials to resist harsh environments such as high temperatures suggest that this device will prove useful in sub-6 GHz harsh environment 5G applications viz. handheld 5G devices and industrial Internet of Things (IoT)-enabled systems in smart cities, automotive, space, and aeronautics applications.

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