

GaAs Optical Field Effect Transistor (OPFET): A High Performance Photodetector for Automotive Applications

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ABSTRACT

Photodetectors are important components in automotive industry. Sensitivity, speed, responsivity, quantum efficiency, photocurrent gain and power dissipation are the important characteristics of a photodetector. We report a high performance photodetector based on GaAs Metal- Semiconductor Field Effect Transistor (MESFET), with very high responsivity, excellent quantum efficiency, high sensitivity, moderate speed, tremendous gain and low power dissipation, surpassing their photodiode, phototransistor and other counterparts. A theoretical model of GaAs front illuminated Optical Field Effect transistor is presented. The photovoltaic and photoconductive effects have been taken into account. The gate of the OPFET device has been left open to make a reduction in the number of power supplies. The results are in line with the experiments. The device shows high potential in automotive applications.

CITATION: Gaitonde, J. and Lohani, R., "GaAs Optical Field Effect Transistor (OPFET): A High Performance Photodetector for Automotive Applications," *SAE Int. J. Passeng. Cars – Electron. Electr. Syst.* 9(1):2016, doi:10.4271/2016-01-0094.

INTRODUCTION

The automotive industry has been equipped with photodetectors for control of headlamps, back lights, dashboard lights, anti-glare mirrors, and windshield wipers. These photodetectors require high sensitivity, responsivity, speed, low power dissipation, etc and should operate at visible or infrared wavelengths depending upon the application. Many field effect transistor (FET)-based photodetectors functioning in the visible-infrared region have recently been reported. The following few paragraphs will give a brief review of some of these photodetectors.

CdS nanobelt (NB) Metal-Semiconductor Field Effect Transistor (MESFET)-based photodetectors showing a photoresponsivity of 2×10^2 A/W corresponding to an external quantum efficiency (EQE) of 5.2×10^2 and rise and decay times of 137 μ s and 379 μ s respectively at 488 nm wavelength at an optical power density of 5.3 mW/cm² were fabricated [1]. An external photoresponsivity of 128 mA/W (internal responsivity of 642 mA/W) was achieved in silicon waveguide integrated germanium Junction Field Effect Transistor (JFET) photodetector under 1550 nm illumination at an optical power of 1.7 mW with a 3 V bias [2]. Black phosphorous FETs showed a responsivity of 4.8 mA/W and a rise time of 1 ms at 640 nm at an optical power of 10 nW at 200 mV drain bias and zero gate bias [3]. Field-effect transistor-based solution-processed colloidal quantum dot photodetector exhibiting broad spectral bandwidth in the Near-Infrared (NIR) region and a responsivity of 0.391 mA/W under 600 nm illumination at an intensity of 30 μ W/cm² was established [4].

CdTe nanowire FETs with a responsivity of 80.1 A/W, a photoconductive gain of 2.5×10^{40} and response and decay times of 0.7 s and 1 s respectively under 400 nm illumination at an optical

power density of 78 μ W/cm² were demonstrated [5]. A photocurrent gain of 9.8 was attained in a photo JFET with a colloidal quantum dot absorber channel layer at 450 nm wavelength at 0.4 μ W optical power at a bias of 30 V [6]. A rise time of 10 μ s was obtained. Pentacene-based photodetector using vertical FET configuration showed a responsivity of 160 mA/W at 400 nm at a drain bias of -2 V [7]. Using a field-effect transistor configuration, a solution-processed NIR photodetector based on PbSe colloidal quantum dots was introduced. It showed a responsivity of 500 A/W at a drain bias and a gate bias of -40 V with 40 mW/cm² of 980 nm illumination [8]. Organic FETs utilizing neodymium phthalocyanine as light sensitive material exhibited a responsivity of 108 A/W (EQE of 20612%) under 650 nm illumination with an optical power density of 5.92 μ W/cm² at a drain bias of 50 V [9].

In this paper, we present a theoretical model of GaAs Optical Field Effect Transistor or Optically Controlled MESFET (OPFET) by considering both photoconductive and photovoltaic effects into account. The first section presents the theory. The continuity equations in the channel and depletion regions have been solved analytically. The channel charge, and depletion charge due to photogeneration as well as charge due to doping have been calculated by numerical integration using Trapezoidal method. The total drain to source current has been computed using the model presented in [10]. The various detector parameters which reveal its performance are calculated. The second section shows the obtained results and their interpretation and analysis. The third section gives a summary or the conclusion of the work done.

The simulations show that the device has better performance in terms of detector responsivity, gain, and quantum efficiency over various detectors reported so far in the visible-NIR region. In addition, it has low power dissipation, low value of switching time and high sensitivity. This detector will be useful for the automotive industry employing visible-infrared photodetectors with benefits to the aerospace and commercial vehicle industries as well.

THEORY

The schematic structure of GaAs OPFET with floating gate is presented in Fig. 1. The substrate material is p-type semi-insulating (SI) GaAs whereas the active layer is of n-type GaAs. The active layer is uniformly doped. The radiation is allowed to fall on the transparent gate of the device. The gate is kept floating. The radiation is absorbed in the channel and substrate regions creating electron-hole pairs. The optically generated electrons move towards the channel while the holes move in the opposite direction. On the application of drain to source voltage, the electrons give rise to drain to source current which increase the conductivity of the channel. The holes crossing the junction develop a photovoltage which reduces the depletion width and in turn increases the drain to source current.

The extension of the Schottky junction depletion region in the channel measured from the surface under illumination is given by [11]

$$y_{dg} = \left[\frac{2\epsilon}{qN_{dr}} \left(\Phi_B - \Delta + v(x) - v_{gs} - V_{OP1} \right) \right]^{\frac{1}{2}} \quad (1)$$

where Φ_B is the Schottky barrier height, Δ is the position of Fermi level below the conduction band, ϵ is the permittivity of GaAs, V_{OP1} is the photovoltage generated across the Schottky junction and $v(x)$ is the channel voltage which varies from 0 at the source end and V_{DS} at the drain end. V_{DS} is the drain to source voltage and v_{gs} is the gate to source voltage.

Since the substrate is made semi-insulating and the channel is moderately doped, the p-n junction depletion width at the channel-substrate interface extends completely into the substrate whereas the depletion width is zero on the channel side. The photovoltage generated across the p-n junction depletion region has no effect on the detector characteristics.

Calculation of Photovoltage

The continuity equation for holes in the Schottky junction depletion region is given by [11]

$$\frac{\partial p}{\partial y} + \frac{p}{v_y \tau_p} - \frac{\alpha \Phi \exp(-\alpha y)}{v_y} = 0 \quad (2)$$

Here p is the hole density, v_y is the carrier velocity in the y-direction, τ_p is the lifetime of holes, α is the absorption coefficient, Φ is the radiation flux density, y is the distance from surface towards the substrate.

The solution of Eq. (2) can be expressed analytically as

$$p(y) = A_1 + \alpha \Phi \tau_p B_1 \left[1 - \frac{1}{(1 - \alpha v_y \tau_p)} \right] \exp \left[-\frac{y}{v_y \tau_p} \right] \quad (3)$$

$$A_1 = \left[\frac{\alpha \Phi \tau_p \exp(-\alpha y)}{(1 - \alpha v_y \tau_p)} \right] \quad (4)$$

$$B_1 = \exp \left[-\left(\alpha - \frac{1}{v_y \tau_p} \right) y_{dg} \right] \quad (5)$$

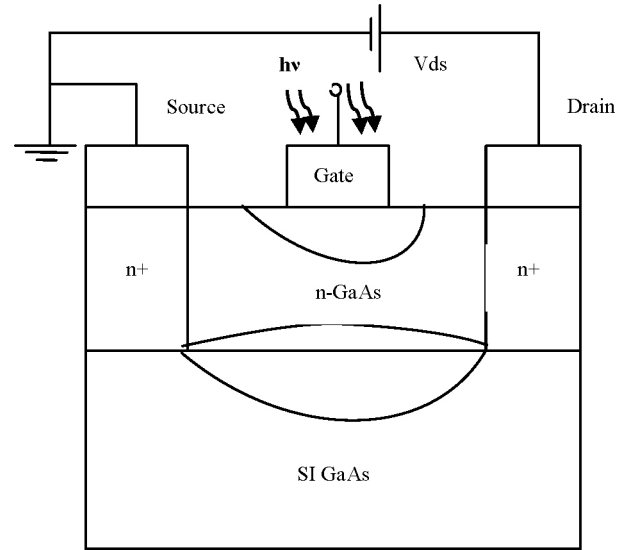


Figure 1. Schematic structure of GaAs OPFET.

using the boundary condition at $y=y_{dg}$,

$$p = \alpha \Phi \tau_p \exp(-\alpha y_{dg}) \quad (6)$$

Then the photovoltage can be calculated as

$$V_{OP1} = \frac{kT}{q} \ln \left[1 + \frac{q v_y p(0)}{J_{s1}} \right] \quad (7)$$

where $p(0)$ is the hole density evaluated at $y=0$, J_{s1} is the reverse saturation current density across the Schottky junction, q is the electronic charge, k is the Boltzmann constant and T is the temperature.

Calculation of Photogenerated Electron Density in the Channel

The continuity equation for electrons in the neutral channel region is represented by [11]

$$\frac{\partial^2 n}{\partial y^2} - \frac{n}{D_n \tau_n} + \frac{\alpha \Phi \exp(-\alpha y)}{D_n} = 0 \quad (8)$$

Here n is the electron density, D_n is the diffusion constant of electrons, τ_n is the lifetime of electrons.

Equation (8) can be solved analytically and its solution is given as

$$n(y) = \alpha \Phi \tau_n A_2 \exp(-\alpha y_{dg}) \exp\left[-\frac{(y - y_{dg})}{L_n}\right] - B_2 \quad (9)$$

$$A_2 = \left[1 + \frac{1}{(\alpha^2 L_n^2 - 1)}\right] \quad (10)$$

$$B_2 = \frac{\alpha \Phi \tau_n \exp(-\alpha y)}{(\alpha^2 L_n^2 - 1)} \quad (11)$$

L_n is the diffusion length of electrons, $L_n = (D_n \tau_n)^{1/2}$.

The boundary condition used is at $y=y_{dg}$,

$$n = \alpha \Phi \tau_n \exp(-\alpha y_{dg}) \quad (12)$$

Calculation of Photogenerated Electron Density in the Depletion Regions

The continuity equation in the depletion region is given by [11]

$$\frac{\partial n}{\partial y} - \frac{n}{v_y \tau_n} + \frac{\alpha \Phi \exp(-\alpha y)}{v_y} = 0 \quad (13)$$

The analytical solution is given as

$$n(y) = \frac{\alpha \Phi \tau_n \exp(-\alpha y)}{(1 + \alpha v_y \tau_n)} \quad (14)$$

Calculation of Drain to Source Current

The total conducting charge is given by,

$$Q_n = Q_d + Q_{ch} + Q_{dep1} + Q_{dep2} \quad (15)$$

Here Q_d is the charge due to doping; Q_{ch} , Q_{dep1} , and Q_{dep2} are the charge due to photogeneration in the channel, Schottky junction depletion region, and substrate depletion region respectively.

Q_n can be calculated as:

$$Q_n = \int_{y_{dg}}^a N_{dr} dy + \int_{y_{dg}}^a n_{ch} dy + \int_0^{y_{dg}} n_{dep1} dy + \int_a^d n_{dep2} dy \quad (16)$$

where n_{ch} , n_{dep1} , and n_{dep2} are the photogenerated electron densities in the channel, Schottky junction depletion region, and substrate depletion region respectively; a is the active layer thickness; d is the surface to substrate thickness.

The total drain to source current is then calculated using the model described in [10]:

$$I_{ds} = I_{dss} (1 + \lambda V_{DS}) \tanh(\eta V_{DS}) + V_{DS} / R_{sh} \quad (17)$$

where the symbols have the same meaning as in [10]. The parasitic source and drain resistances involved in the calculation are obtained following a similar procedure as given in [12].

All the integrations concerned with the computation of charge are performed numerically using Trapezoidal method.

Since the gate is kept open, there is no leakage current flow at the gate junction. The operating ambient temperature may have impact on the device performance. However, it is subject to a separate and independent topic and beyond the scope of this paper.

Calculation of Detector Parameters

Responsivity [13]

$$R = \frac{I_{ph}}{P} \quad (18)$$

I_{ph} is the photocurrent and P is the incident optical power.

$(P = ZL\Phi h\nu / [(1 - r_s)(1 - r_m)])$, h is the Planck's constant, ν is the frequency of radiation, r_m is the reflection coefficient at the metal entrance and r_s is the reflection coefficient at the metal semiconductor interface.

Quantum Efficiency [13]

$$EQE = \frac{I_{ph} h\nu}{qP}$$