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# Analysis of triple metal surrounding gate (TM-SG) III–V nanowire MOSFET for photosensing application

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ABSTRACT

In this paper, a low power highly sensitive Triple Metal Surrounding Gate (TM-SG) Nanowire MOSFET photosensor is proposed which uses triple metal gates for controlling short channel effects and III–V compound as the channel material for effective photonic absorption. Most of the conventional FET based photosensors that are available use threshold voltage as the parameter for sensitivity comparison but in this proposed sensor on being exposed to light there is a substantial increase in conductance of the GaAs channel underneath and, thereby change in the subthreshold current under exposure is used as a sensitivity parameter (i.e., $I_{illumination}/I_{Dark}$). In order to further enhance the device performance it is coated with a shell of $Al_xGa_{1-x}As$ which effectively passivates the GaAs surface and provides a better carrier confinement at the interface results in an increased photoabsorption. At last performance parameters of TM-SG Bare GaAs Nanowire MOSFET are compared with TM-SG core-shell GaAs/AlGaAs Nanowire MOSFET and the results show that Core-Shell structures can be a better choice for photodetection in visible region.



## 1. Introduction

From decades, one golden rule has guided the entire microelectronics world, the downscaling of the Metal Oxide Semiconductor Field Effect Transistor (MOSFET). Downscaling the device degrades the gate controllability over the channel and has the disadvantage of increased short channel effects (SCE's) [1,2]. Several novel design structures has been proposed to extend device scaling down to nanometer regime [3–6]. Out of those novel device structures Multigate MOSFET's proved to be one of the most effective solutions to reduce SCE's. In several Multigate structures, Gate-All-Around (GAA) Nanowire MOSFETs have a better electrostatic coupling between gate and the channel as gate electrode completely surrounds the channel which in turn reduces off state leakage current and provides immunity from short channel effects (SCEs) [7–9]. Many authors in the recent past have also reported gate stack engineering [10,11] an effective way to reduce off state leakage current which provides a pathway to scale down beyond 45 nm as reported in International Roadmap to Semiconductor [12,13]. Despite using high-k dielectrics, SCE's is still a problem when channel length reduces further down. Authors have also suggested that Gate Material engineering can be one of the effective solution for down scaling further down to 20 nm [14]. Dual Material Surrounding Gate MOSFET (DMSG) has been proposed which improves SCE's as compared to Single Material Surrounding Gate [15]. Recently, triple material(TM)in SG MOSFET isreported by Wang et al. [16] in which a formation of two-step potential in the channel allows further gate length scaling which effectively diminishes the SCEs as compared with both Single Metal and Dual Metal MOSFET.

Semiconductor nanowires have gained much attention in the near past for their novel photonic, electronic, mechanical, thermal and electrical properties [17–20]. Semiconductor nanowires have one dimensional structure possess large surface to volume ratio [21] which can be utilized in the effective confinement of light energy and, hence, this unique feature is favourable in the designing of highly sensitive photodetectors, optical interconnects, and solar cells [22–24]. As compared to a indirect band gap semiconductor (e.g., Si), a direct band gap semiconductor nanowire III–V compound such as Gallium Arsenide (GaAs) has an advantage of absorbing light energy more efficiently. MOSFETs made up of GaAs as the channel material also offer very high carrier mobility [25]. As bare GaAs Nanowire has large density of surface states because of its inherent geometry which in turn severely degrades device characteristics by pinning the surface Fermi energy [26–28]. So in order to prevent device degradation in bare GaAs is coated with shell of $Al_xGa_{1-x}As$ that passivates the non radiative charge trap-

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swhich and decreases surface scattering results in higher carrier transport efficiency [29,30]. Also, it is found that a tri-metal gate nanowire MOSFET with gate stack provides high performance in analogue and RF application [31]. Moreover, a simplified compact model, comprising quantum effects for cylindrical nanowire MOSFET was developed by Ragi et al. [32], which reduces the complexity involved in previous models.

In this paper, to incorporate the effect of both Triple Metal Gate and III–V compound channel material, we demonstrate a Triple Metal Surrounding Gate III–V Nanowire MOSFET (TM-SG) photosensor in which triple metal gate with different work functions are used to enhance carrier transport proficiency. Higher work function metal is placed near the source end to accelerate the charge carrier inside the channel [30]. Lower work function metal is placed near the drain end which will reduce the peak electric field at the drain side and, hence, results in a reduced Hot Carrier Effect [30]. GaAs is used as the device material for effective absorption of light energy in the desired region of spectrum. GaAs being a direct bandgap semiconductor absorbs light more efficiently as compared to indirect bandgap materials. Further the impact of encapsulation of GaAs with $Al_xGa_{1-x}As$ acting as a shell is studied on photosensitivity and Quantum Efficiency.

## 2. Device structure and simulation setup

Figure 1(a) depicts the 2D-cross section view of TM-SG GaAs MOSFET, Figure 1(b) depicts the 2D-cross section view of TM-SG Core-Shell GaAs/AlGaAs MOSFET and Figure 1(c) depicts the 3D-simulated structure of TM-SG MOSFET under incident radiation. R is the radius of channel, L is the channel length, $L_S$ is the source length, $L_D$ is the drain length, z is the channel direction, and $t_{ox}$ is the oxide thickness and $L_1$, $L_2$, $L_3$ are the lengths of Metal Gates.

In order to extricate device characteristics under dark and under incident radiationa SILVACO ATLAS-3D simulator [33] is used to simulate TM-SG III–V Nanowire MOSFET. The parameters used in the simulation process are as given in Table 1. It also incorporates an advance LUMINOUS-3D optical device simulator to extricate device characteristics under incident radiation which uses Ray Trace method for calculating the photogeneration rate at defined mesh points. The optical parameters for the incident radiation such as radiation intensity, wavelength and location is set by using a BEAM keyword incorporated in a LUMINOUS-3D module. Various models used for the purpose of simulation of TM-SG III–V NanowireMOSFET are: Shockley Read Hall model (SRH) and Bohm Quantum Potential (BQP) with parameters of alpha = 0.5 and gamma = 1.2. SRH model accounts for the chances of recombination phenomenon at traps and BQP model accounts for the inclusion of quantum effects as the radius of the device is less than 5 nm, quantum mechanical effects cannot be neglected [34].

The path of light from air to the channel underneath in Bare GaAs is obstructed due to reflections at three interfaces namely air to gate metal, gate metal to oxide layer and oxide layer to GaAs. For a Core-Shell GaAs-AlGaAs structure one additional interface from oxide layer to AlGaAs is added. Reflection at theses interfaces helps analyzing the behaviour of the device under incident radiation. The reflection coefficients for these three interfaces can be calculated using the formula [35]:

$$R_c = \frac{(n_c - n_{c+1})^2 + {k_{c+1}}^2}{(n_c + n_{c+1})^2 + {k_{c+1}}^2} \tag{1}$$

where $R_1$, $R_2$ and $R_3$ are the reflection coefficients at the three interfaces, i.e., air to metal gate, metal gate to oxide layer and oxide layer to semiconductor respectively. $n_1$, $n_2$, $n_3$ and $n_4$ are the real part of refractive index of air, gate metal, oxide layer and semiconductor, respectively, and $k_c$s are the corresponding imaginary part of the refractive indices. SOPRA database [36] is referred to get the real and imaginary values of the refractive index in order to calculate the reflection coefficients for the purpose of simulation of TM-SG III–V Nanowire MOSFET under incident radiation. Table 2 shows the real and imaginary refractive index values for Oxide Layer ($Al_2O_3$), GaAs and AlGaAs for different wavelengths of incident radiation. It also shows the values of absorption coefficient ($\alpha$) for GaAs and AlGaAs for different wavelengths.

The amount of incident light being absorbed by the GaAs channel underneath which results in the generation of electron-hole pairs (EHP) depends mainly on the absorption coefficient of GaAs denoted by the absorption coefficient ($\alpha$). The parameter $\alpha$ for GaAs has different values for different wavelengths ($\lambda$) of incident radiation and generally decreases with higher wavelengths [35,37].

Rate of generation of EHP depends upon the absorption of incident radiation by the GaAs channel underneath. As mentioned above the generation rate depends on the absorption coefficient of the photosensitive material which is GaAs in our device. The rate of generation of EHP is given by the formula [38]:

$$G_r = \alpha\phi_d \tag{2}$$

**Table 1**
Parameters utilized in simulation process.

| Symbol | Definition | Value |
|---|---|---|
| L | Channel length | 21 nm |
| R | Channel radius | 2.5 nm |
| $L_S$ | Source length | 20 nm |
| $L_D$ | Drain length | 20 nm |
| EOT | Equivalent Oxide thickness | 0.7 nm |
| $N_A$ | Channel doping | $1 \times 10^{16}$ cm$^{-3}$ |
| $N_D$ | Source/Drain doping | $1 \times 10^{20}$ cm$^{-3}$ |
| $L_1$ | Length of 1st Metal Gate | 7 nm |
| $L_2$ | Length of 2nd Metal Gate | 7 nm |
| $L_3$ | Length of 3rd Metal Gate | 7 nm |
| $Ø_1$ | Work Function of 1st Metal Gate | 4.8 eV |
| $Ø_2$ | Work Function of 2nd Metal Gate | 4.6 eV |
| $Ø_3$ | Work Function of 3rd Metal Gate | 4.4 eV |
| $R_c$ | Radius of Core | 1.25 nm |
| $R_s$ | Radius of Shell | 1.25 nm |

**Table 2**
Refractive Indexes of materials used in the simulation of TM-SG Nanowire MOSFET.

| Wavelength (μm) | $Al_2O_3$ | | $Al_xGa_{1-x}As$ (x = 0.33) | | | GaAs | | |
|---|---|---|---|---|---|---|---|---|
| | n | k | n | k | α (cm$^{-1}$) × $10^6$ | n | k | α (cm$^{-1}$) × $10^6$ |
| 0.25 | 1.8452 | 0 | 2.3924 | 3.8898 | 1.9552 | 2.7760 | 4.2690 | 2.145800 |
| 0.30 | 1.8144 | 0 | 3.7147 | 1.9907 | 0.8338 | 3.8170 | 1.9460 | 0.815140 |
| 0.35 | 1.7972 | 0 | 3.6850 | 2.0257 | 0.7273 | 3.5920 | 1.9610 | 0.704085 |
| 0.40 | 1.7865 | 0 | 4.8247 | 1.5539 | 0.4881 | 4.4590 | 2.0810 | 0.653770 |
| 0.45 | 1.7794 | 0 | 4.3399 | 0.5077 | 0.1417 | 4.8580 | 0.7550 | 0.210840 |
| 0.50 | 1.7742 | 0 | 4.0148 | 0.2956 | 0.0074 | 4.3070 | 0.3760 | 0.094499 |
| 0.55 | 1.7704 | 0 | 3.8466 | 0.2158 | 0.0049 | 4.0580 | 0.2680 | 0.061232 |
| 0.60 | 1.7675 | 0 | 3.7305 | 0.1598 | 0.0033 | 3.9120 | 0.2140 | 0.044820 |
| 0.65 | 1.7651 | 0 | 3.6531 | 0.1136 | 0.0021 | 3.8250 | 0.1780 | 0.034413 |