A novel photonic modulator based on an AlGaN/GaN High Electron Mobility Transistor (HEMT)

Pallabi Das, Tian-Li Wu, and Siddharth Tallur

1AIMS Lab, Department of Electrical Engineering, Indian Institute of Technology (IIT) Bombay, Mumbai 400076, Maharashtra, India
2International College of Semiconductor Technology, National Chiao Tung University, 30010 Hsinchu, Taiwan
*stallur@ee.iitb.ac.in

Abstract: We present an electro-optic modulator design concept based on a High Electron Mobility Transistor (HEMT) architecture. The device utilizes the plasma dispersion effect of the highly localized 2D electron gas (2DEG) at the III-V heterojunction as the modulation mechanism. The proposed modulator benefits from the large mobility of the 2DEG carriers that enables ultrahigh speed switching of the carrier density for electro-optic modulation. We derive an analytical model and perform supporting technology computer-aided design (TCAD) simulations using Silvaco ATLAS to quantify the plasma dispersion effect and modulation efficiency due to the 2DEG, and present a feasible parameter space for designing an AlGaN/GaN free-space optical modulator operating at telecommunication wavelength (1.55 µm) for high speed on-chip optical interconnects.

1. Introduction

In the last few decades, fiber optic communication has become the technology of choice for high speed communication links with capacities of several hundreds of gigabits per second (Gbps) and low signal losses over link lengths of thousands of kilometers [1,2]. While fiber optic communication forms a large part of the backbone for communication systems, a critical bottleneck continues to be the interconnects required in short-reach communication. Conventionally used on-chip electrical interconnects are limited to maximum data rates < 10 Gbps due to parasitic capacitance of signal traces [3,4]. Silicon photonics has drawn immense interest over the years owing to the electronic-photonic integration and CMOS-compatibility [5–8]. Although silicon is not an electro-optically active material, it can be used as an electro-optic (EO) modulator by exploiting carrier injection or plasma dispersion effect, when used in p-i-n (p-type/intrinsic/n-type layers) device configuration [5,9,10]. However the carrier recombination lifetime of free charge carriers limits the operating speeds up to ≈ 50 – 60 Gbps in such devices [11], and higher bandwidth applications require wavelength division multiplexing [12]. Alternative modulation mechanisms utilizing other materials compatible with silicon technology e.g. germanium, have been demonstrated to achieve more efficient modulation [13]. Si-Ge multi-quantum well (MQW) electro-absorption modulators exploiting the quantum confined stark effect (QCSE) and Franz-Keldysh effect have also been reported [5,14,15]. QCSE has also been explored in III-V intersubband opto electronic devices [16,17], despite the processing challenge it imposes in terms of incorporating the multi-quantum well structure into the device layer stack. Another alternative technology platform gaining momentum in recent years is lithium niobate (LiNbO₃). Unlike silicon, LiNbO₃ has strong electro-optic (EO) or Pockels effect, which is characterized as change in material refractive index by the application of an electric field. Lithium niobate electro-optic modulators have recently been demonstrated operating at frequencies exceeding 100 Gbps [18].
While most commercial optical modulator products also employ lithium niobate, the material compatibility with other platforms fundamentally limits the scope of on-chip interconnect applications of this technology. Another limitation for high speed on-chip communication arises due to gain-bandwidth performance limits of transistors in any CMOS technology node. For any transistor technology node, the RF performance depends on the cut-off frequency ($f_T$) and the maximum operating frequency of the device ($f_{\text{max}}$). Compared to the highest speed silicon CMOS transistors, gallium nitride (GaN) based High Electron Mobility Transistors (HEMTs) are emerging as a commercially viable technology for high-speed and high-power applications [19]. GaN based HEMT is superior to silicon CMOS transistors because of the rich material properties of GaN such as large band gap (3.4 eV), high saturation velocity ($2.5 \times 10^5$ m/s), high electron mobility ($1600$ cm$^2$/V·s) and higher breakdown field ($330$ MV/m) [16, 20]. The growth of GaN in the semiconductor industry is not only limited to high-power electronics and radio-frequency (RF) devices, but it is also a key driver in opto-electronics and monolithic microwave integrated circuits [21, 22]. In this paper, we propose an electro-optic modulator design inspired by a III-V HEMT used in high speed RF circuits, compatible with all such GaN technology processes. We present a modified Drude model to analyze the change in refractive index due to the perturbation of 2DEG concentration at the III-V interface. We compare our model to TCAD (Technology computer-aided design) simulations performed using Silvaco ATLAS interactive tool for analyzing the electrical and optical properties of the heterostructure.

2. Principle of operation of the proposed modulator

GaN based HEMT consists of two different materials with different band gap e.g., GaN and any ternary alloy such as AlGaN, InGaN etc. Most group III and group V materials with Wurtzite crystal structure exhibit spontaneous and piezoelectric polarization due to inherent non-centrosymmetricity [23]. A potential well is formed at the AlGaN/GaN interface due to the difference in the material band gap. This results in confinement of electrons in the potential well due to the presence of piezoelectric and spontaneous polarization in the two materials. The electrons exist in form of a tightly confined sheet of polarization charge at the interface, functionally behaving as a 2D electron gas (2DEG). Due to isolation from the bulk lattice, these 2DEG carriers have high mobility $1500$ cm$^2$/V·s [24], and large lifetimes and result in much higher speed of operation in HEMTs as compared to Si MOSFETs [16]. The proposed modulator utilizes the 2DEG sheet charge $n_{2\text{DEG}}$ at the AlGaN/GaN heterostructure interface for optical modulation through the plasma dispersion effect. We explore a device configuration wherein the 2DEG carrier density is modulated via external gate voltage applied to a depleted Schottky diode [25, 26].

Our proposed device structure is conceptually similar to a AlGaN/GaN HEMT as shown in Figure 1(a). The top AlGaN layer is used as cladding and the GaN layer serves as core. The device manifestation that we consider for electrical and optical analysis consists of a free-space light beam interacting with the heterostructure. To engineer the plasma dispersion effect, the device requires large overlap of 2DEG region with light confined in the device. The light beam is incident normal to the wafer, reflects from the bottom surface of the wafer and thereby interacts with the 2DEG twice (upon incidence and post reflection) as shown in Figure 1(a). Figure 1(b) schematically describes the simulation process steps required for the analysis of 2DEG and effective refractive index. Figure 1(c) illustrates the frequency spectrum expected at the output of the modulator, showing two side band frequencies separated from the frequency of laser ($\omega_l$) by the signal applied to the gate ($\omega_g$). Modulating the gate voltage applied to the Schottky contact causes modulation of the 2DEG concentration. The 2DEG can be completely depleted to turn off the modulator, and a sufficiently large gate voltage can be applied to introduce 2DEG carriers to turn on the modulator. Modulation
Fig. 1. Illustration of light modulation in free space AlGaN/GaN electro-optic modulator. (a) Incident light falling normally on the wafer gets reflected from the bottom surface of the wafer and thereby interacts with the 2DEG twice (upon incidence and post reflection). By application of a gate voltage 2DEG charge carriers concentrations are changed, which changes material refractive index. Change in refractive index in the material causes phase shift in the light beam interacting with the 2DEG charge carrier region. (b) Illustration of the simulation process flow followed in this work. (c) Schematic of optical frequency sidebands generated by the electro-optic modulator centered about the laser frequency ($\omega_l$) and separated by the frequency of the AC signal applied to the gate ($\omega_g$).

of the 2DEG sheet charge density results in modulation of the refractive index at the AlGaN/GaN interface due to plasma dispersion effect. The variation of effective refractive index with free carrier concentration is quantified by developing a modified Drude model as described in section 3.1. By changing the effective refractive index, phase shift ($\Delta \phi$) can be introduced in the light beam, which is expressed as:

$$\Delta \phi = \frac{2\pi}{\lambda} (2t \times \Delta n_{2DEG})$$

where $t$ is the thickness of the 2DEG region, and $\Delta n_{2DEG}$ is the change in refractive index due to the 2DEG plasma dispersion effect. For a practical device, the phase shift for peak-peak applied modulating voltage should be $\pi$ radians, and thereby such a device should be embedded in a photonic resonator with Mach-Zehnder Interferometer (MZI) [5, 18] (Figure 2 (a)), or a high finesse Fabry Perot cavity (Figure 2 (b)) to increase the number of round trips through the 2DEG, thereby amplifying the phase shift.

The Mach-Zehnder Interferometer based waveguide modulator concept is illustrated in Figure 2(a). The same modulation principle is applicable to this configuration, with an additional requirement that the device dimensions be designed to define a single mode waveguide. The section below presents a detailed electro-optic TCAD simulation framework in Silvaco ATLAS for determining the performance parameters of the free space modulator. In order to calculate the change in refractive index with gate bias, we need to first calculate the variation of 2DEG charge carrier concentration with varying gate voltage. Therefore, we follow the simulation process flow illustrated in Figure 1(b).
3. Device physics model

3.1. Analytical model

The Drude plasma model provides the dependence of complex refractive index \( n + ik \) of a material on the free carrier concentration in the semiconductor, where \( n \) and \( k \) denote the real and imaginary part of the refractive index respectively. The analytical expressions for the plasma dispersion effect \( \Delta n \) and free-carrier absorption \( \Delta k \) at a wavelength \( \lambda \) are given by [27]:

\[
\Delta n = \frac{-e^2 \lambda^2}{8\pi^2 c^2 \varepsilon_o n} \left( \frac{\Delta N}{m_{ce}^*} + \frac{\Delta P}{m_{ch}^*} \right) 
\]

\[
\Delta k = \frac{e^3 \lambda^3}{6\pi^3 c^3 \varepsilon_o n} \left( \frac{\Delta N}{\mu_e m_{ce}^*} + \frac{\Delta P}{\mu_h m_{ch}^*} \right) 
\]

where, \( \Delta N \) and \( \Delta P \) are the free-carrier densities, \( \mu_e \) and \( \mu_h \) are the mobility and \( m_{ce}^* \) and \( m_{ch}^* \) are the conductivity effective mass for electrons and holes respectively, \( e \) is the electron charge, \( c \) is the speed of light, \( \varepsilon_o \) is the permittivity of vacuum, and \( n \) is the real part of refractive index of the undoped semiconductor. From equations (2) and (3) we can calculate the carrier induced electro-refraction and electro-absorption respectively.

Since we consider undoped AlGaN and GaN, the contribution to refractive index modulation due to free carriers is assumed to be negligible in the bulk. The refractive index modulation is thereby assumed to be dominated by modulation of the 2DEG charge density on account of the gate voltage, and we ignore the contribution of free-carrier concentration terms in the Drude model. The modified Drude model, accounting solely for the change in real part of the refractive index \( \Delta n_{2DEG} \) due to change in 2DEG charge density \( \Delta N_{2DEG} \) is given by equation (4):

\[
\Delta n_{2DEG} = \frac{-e^2 \lambda^2}{8\pi^2 c^2 \varepsilon_o n} \left( \frac{\Delta N_{2DEG}}{m_{ce}^*} \right) 
\]

To derive an expression for \( \Delta n_{2DEG} \) in terms of applied gate voltage, we first simulate the variation of \( N_{2DEG} \) for different bias conditions in Silvaco ATLAS. The source and drain region contacts are connected to ground and the DC gate voltage is swept in a range covering pinch off to enhancement. The 2DEG sheet charge density variation with gate voltage for different molar concentration of Al (\( x \) in Al\(_x\)Ga\(_{1-x}\)N) is obtained from the simulation, as shown in Figure 3 (a detailed description of the simulation setup is provided in section 3.2). The bound sheet charge density due to piezoelectric (denoted by superscript \( pz \)) and spontaneous polarization (denoted by superscript \( sp \)) at the AlGaN/GaN interface can be expressed as:

\[
\sigma_b = P_{GaN} - P_{AlGaN} = P_{GaN}^{sp} + P_{GaN}^{pz} - P_{AlGaN}^{sp} - P_{AlGaN}^{pz} 
\]
The piezoelectric polarization for GaN layer is considered to be zero, as the thickness of the GaN layer is much larger (typically few \(\mu m\)) than that of the AlGaN layer (typically few tens of \(nm\)) [28]. Also, the magnitude of the spontaneous polarization of AlGaN is much larger than that of GaN. So, the bound sheet charge contribution is solely on the account of spontaneous and piezoelectric polarization of AlGaN layer. Higher Al concentration produces large polarization difference, which in turn gives rise to higher sheet charge density at the interface, and is also observed in Figure 3. For obtaining higher electron concentration, we have selected 30% Al molar concentration in Al\(_x\)Ga\(_{1-x}\)N for simulation in all subsequent discussions in this paper, unless otherwise mentioned.

![Fig. 3. TCAD simulation showing 2DEG sheet charge concentration for different Al molar concentration. The polarization difference increases with increasing Al concentration, thus giving rise to higher sheet charge density at the AlGaN/GaN interface. TCAD simulation yields the volume charge density of 2DEG. In this plot the volume charge density is multiplied with the lateral depth of 1\(\mu m\) to get the surface charge density.](image)

The analytical expression for \(N_{2DEG}\) dependence on gate voltage \((V_g)\) has been extensively studied in literature [29–33]. The approximate relations available in literature for relating \(N_{2DEG}\) to \(V_g\) are only valid for the linear region of operation in a HEMT. Our proposed modulator relies on both depletion as well as linear regions of operation, and hence these models are not adequate, and hence we solve the Poisson’s equation [31] for our device structure. Assuming the AlGaN layer is completely ionized and solving Poisson’s equation for metal/i-AlGaN/i-GaN layer, we obtain:

\[
N_{2DEG} = \frac{C_d}{q}[(V_g - V_{off}) - V_c - E_f]
\]

where \(C_d\) is the effective capacitance per unit area between the gate electrode and 2DEG, \(V_c\) is the voltage at drain or source contact and \(E_f\) is the Fermi energy level. The term \(V_{off}\) denotes the pinch-off voltage, below which the 2DEG is completely depleted. The complexity in modeling the 2DEG charge density arises due to the fact that the Fermi level \(E_f\) in equation (6) is also a function of \(N_{2DEG}\) and can be expressed as a transcendental equation [32] as shown below:

\[
N_{2DEG} = D V_l n\left[\exp\left(\frac{E_f - E_0}{k T / q}\right) + 1\right] + n\left[\exp\left(\frac{E_f - E_1}{k T / q}\right) + 1\right]
\]

where \(D\) is the density of states, \(k\) is the Boltzmann constant, \(E_0 = \gamma_0 N_{2DEG}^{2/3}\) and \(E_1 = \gamma_1 N_{2DEG}^{2/3}\) are energies of the two lowest subbands. We assume only two discrete energy levels \(E_0\) and \(E_1\) present at the potential well formed at the interface. A charge control model is also been
proposed by Khandelwal et al. [31], for AlGaN/GaN HEMT, by simplifying the basic device equations in different regions of operation. However this model does not have any empirical or fitting parameters. A precise analytical expression for \( N_{2DEG} \) as a function of \( V_g \) has been proposed by Dasgupta et al. [33] for AlGaAs/GaAs HEMT. We have used similar methodology to derive the analytical model of \( N_{2DEG} \) vs \( V_g \) for AlGaN/GaN HEMT structure. We represent \( E_f \) as a function of \( N_{2DEG} \) as a polynomial expression given in equation 8 [33] and then a curve fitting technique is used to obtain the relation of \( N_{2DEG} \) and \( V_g \).

\[
E_f = k_1 + k_2 N_{2DEG}^{1/2} + k_3 N_{2DEG} \tag{8}
\]

Substituting equation (8) in equation (6), we obtain:

\[
N_{2DEG} = \left\{ \frac{-k_2 + \sqrt{k_2^2 + 4 k_3' (V_g - V_{off} - k_1) \frac{1}{2}}} {2 k_3'} \right\}^2 \tag{9}
\]

where

\[
k_3' = k_3 + \frac{qd_{AlGaN}}{\epsilon} \tag{10}
\]

\( q \) is the electronic charge and \( d_{AlGaN} \) is the AlGaN layer thickness. The off voltage observed for 30% Al molar concentration in \( Al_xGa_{1-x}N \) from the simulation (shown in Figure 3) is in agreement with the measured data obtained by Yvon Cordier et al. [34]. However the charge carrier concentration reported in [34] is lower than what we observed in our simulation. It is to be noted that the simulation parameters are obtained for an ideal AlGaN/GaN HEMT structure with no interface traps, dislocations or any other defects. In simulation the polarization charge can also be calibrated by using polar.scale. The detail analysis of the parameter is given in section 3.3.

3.2. Electrical simulation of 2DEG concentration variation with gate voltage

To obtain the value of \( V_{off} \), we analyze the capacitance-voltage (C-V) profile of the heterostructure. Below \( V_{off} \), the device presents an additional depletion capacitance, and hence the C-V profile simulation is useful for estimating the pinch-off voltage \( (V_{off}) \) to identify the operating bias point of the modulator. TCAD simulation of C-V profile is setup by applying an ac voltage of frequency 1MHz in Silvaco ATLAS, and the parameters used for the simulation are listed in Table 1.

| Parameters        | Gate electrode | Barrier layer | Channel layer |
|-------------------|----------------|---------------|---------------|
| Material          | Schottky metal | \( Al_{0.3}Ga_{0.7}N \) | GaN           |
| Thickness         | 500nm          | 25nm          | 1.475 \( \mu m \) |
| Length            | 4\( \mu m \)   | 10\( \mu m \) | 10 \( \mu m \) |

Table 1. Parameters used for TCAD simulation to obtain C-V profile of the heterostructure and \( N_{2DEG} \) variation with \( V_g \).

The 2DEG sheet charge density and capacitance voltage measurements are carried out for AlGaN/GaN HEMT with Al molar concentration of 30% and a barrier thickness of 25nm. We consider a depletion mode i-AlGaN/i-GaN HEMT structure consisting of a metal Schottky contact, and Ohmic drain and source contact (see Figure 2(c)). Consider the case where the Schottky contact is biased at the edge of depletion region \( (V_{off}) \). The thin depleted AlGaN layer
between the top Schottky and the bottom 2DEG sheet charge can be considered as a parallel plate capacitance ($C_j$), for gate voltage $V_g > V_{off}$ (as shown in Figure 4(a)). This capacitance can be expressed as:

$$C_j = \frac{\varepsilon_r \varepsilon_0 A}{d_{AlGaN}}$$

where $\varepsilon_0$ and $\varepsilon_r$ are the permittivity of free space and relative permittivity of the AlGaN layer respectively, $A$ is the area under the gate electrode and $d_{AlGaN}$ is thickness of the AlGaN layer. Upon application of a reverse bias voltage, the 2DEG is depleted and for gate voltage $V_g < V_{off}$ the heterostructure presents an additional depletion capacitance ($C_{2DEG}$). The net capacitance thus reduces at pinch-off as illustrated in Figure 4(b). The total capacitance ($C_{tot}$) in the pinch-off region is given by [5,25]:

$$C_{tot} = \frac{C_j \times C_{2DEG}}{C_j + C_{2DEG}}$$

The modulator is turned off by reducing the gate voltage below $V_{off}$, and is turned on by increasing the gate voltage sufficiently above $V_{off}$ to have large 2DEG concentration in the channel. Figure 5 shows the simulated C-V profile of the device. The value of $V_{off}$ for the device parameters specified in Table 1 is obtained from simulation to be $-6V$, which can be feasibly achieved in a practical implementation. The values for $k_1$, $k_2$, and $k_3$ that appear in equation 9 are obtained from curve fitting: $k_1 = -0.10101$, $k_2 = 4 \times 10^{-9}$, $k_3 = 3 \times 10^{-15}$. Figure 6 confirms that the simulated curve and the derived analytical model show good agreement with each other.

### 3.3. Simulation of effective refractive index using TCAD simulation in Silvaco ATLAS

We use two approaches to find the relation of $\Delta n_{2DEG}$ to $V_g$. The first approach is a hybrid TCAD-analytical approach, wherein we obtain the relation of $N_{2DEG}$ to $V_g$ from TCAD, and then substitute the values in modified Drude model as given by equation (4). A simulation model of polarization charge analysis for various barrier thickness and Al concentration values in an AlGaN/GaN HEMT device has already been implemented as a built-in example in ATLAS [35]. We adapt this example to our device design and obtain a plot for the 2DEG carrier concentration variation with gate voltage as shown in Figure 7. It is important to note that the 2DEG concentration is typically specified as a surface charge density. However, the notation used in equation (4) indicates the volume charge density of the 2DEG. This is consistent with TCAD simulation which also yields a volume charge density while extracting the value of 2DEG [35]. To obtain the 2DEG surface charge density, we multiply the volume charge density with the
Fig. 5. Simulated capacitance-voltage profile of the AlGaN/GaN heterostructure. When the channel is present, the thin depleted AlGaN layer between the Schottky metal (top electrode) and the 2DEG (bottom electrode) forms a parallel plate capacitance ($C_j$). Below off-voltage, there is an additional series capacitance due to the depleted 2DEG.

Fig. 6. Variation of $N_{2DEG}$ with gate bias voltage ($V_g$): simulated (solid line) and analytical model (dotted line). Both curves show good agreement with each other. The surface charge density is obtained by multiplying the lateral depth of 1µm with the volume charge density obtained from TCAD simulation.
lateral depth of the device (along a direction normal to the plane of the paper), which is assumed to be 1µm [35].

![Graph](image)

Fig. 7. (Black, left Y-axis) Variation of 2DEG charge density ($N_{2DEG}$) with applied gate bias ($V_g$), (Blue, right Y-axis) Variation of slope of ($N_{2DEG}$)−$V_g$ curve ($\frac{\partial N_{2DEG}}{\partial V_g}$) with gate bias voltage. In this plot we show the volume charge density in order to be consistent with the electron concentration value used in Drude model.

Figure 7 also shows the simulated 2DEG charge density vs gate voltage ($V_g$), and the derivative of the curve. The derivative ($\frac{\partial N_{2DEG}}{\partial V_g}$) is for estimating $\Delta N_{2DEG}$, which can be related to the slope of the curve and the applied gate voltage $V_g$:

$$\Delta N_{2DEG} = \frac{\partial N_{2DEG}}{\partial V_g} \Delta V_g$$  \hspace{1cm} (13)

The derivative of the $\Delta N_{2DEG} − V_g$ curve is computed in Origin Lab, using the $N_{2DEG} − V_g$ simulation data obtained from Silvaco ATLAS. Considering the modulating voltage peak-peak amplitude to be $V_{drive} = 1V_{p-p}$ and operating wavelength $\lambda = 1.55\mu m$, we obtain $\Delta n_{2DEG} \approx -7.39 \times 10^{-3}$, corresponding to a change of 2DEG carrier concentration $\Delta N_{2DEG} \approx 3.5 \times 10^{14} \text{cm}^{-2}$. The values of other parameters are chosen as $n_{GaN} = 2.31$ and $m^*_c,2DEG = 0.22 \times m_e \approx 9.1 \times 10^{-31} \text{kg}$. This results in a phase shift $\Delta \phi_{2DEG} \approx -5.99 \times 10^{-5}$ radians. The order of magnitude of the variation in refractive index is comparable to silicon based plasma dispersion modulators and hence for a practical application (with π phase shift for peak-peak applied modulating voltage), such a device should be embedded in a high finesse Fabry Perot cavity, or photonic resonator with Mach Zehnder Interferometer (MZI) [5,18] to increase the number of optical round trips through the 2DEG.

The second approach we follow relies on simulating the modified Drude model within Silvaco ATLAS. TCAD simulation for Si optical modulator in a p-i-n waveguide configuration is provided as a built-in example in ATLAS [37]. The example model implements free carrier plasma dispersion effect using ABS.FCARRIER model. The model also simulates the change in effective refractive index with applied bias voltage using WCGD.REFR parameter and WAVEGUIDE statement to define geometry and physical models for a stand-alone optical mode simulation. The parameters of the free carrier Plasma dispersion model can be modified for different materials using FC.AN, FC.AP, FC.RN, FC.RP etc. parameters in the MATERIAL section. For detail explanation of the terms and glossary, readers are encouraged to read the Atlas User’s Manual [38]. Drude plasma model based on the free carrier plasma dispersion effect has also been reported in literature for simulation of an optical modulator with a MOS junction using Silvaco Atlas [39], where free carrier electro-refraction ($\Delta n$) and electro-absorption ($\Delta k$) models have been implemented using ABS.DR尤DE parameter. We adapt these same model for our device
simulation. Various material properties such as electron effective mass, mobility and refractive index for different materials can be overridden manually by using DRUDE.ME, DRUDE.MUE, REAL.INDEX and IMAG.INDEX respectively in the MATERIAL statement. The parameters and their values used for this simulation are listed in Table 2.

| Description                  | Parameter       | Value          | Remarks                                                                 |
|------------------------------|-----------------|----------------|-------------------------------------------------------------------------|
| Electron effective mass      | DRUDE.ME        | 0.22           | $m^*_{c,2DEG} = 0.22 \times m_e$                                       |
| Electron mobility            | DRUDE.MUE       | 1000$\text{m}^2/\text{V.s}$ | The value of the conduction band electron mobility is overridden by 2DEG mobility in Drude model |
| Refractive index of GaN      | REAL.INDEX      | 2.31           | For wavelength $\lambda = 1.55\mu m$                                   |
| Refractive index of Al$_x$Ga$_{1-x}$N | REAL.INDEX | 2.30           | For wavelength $\lambda = 1.55\mu m$ and $x = 0.3$                     |
| Polarization charge          | polar.scale     | 1.1            | To modify the sign and magnitude of polarization charge (default = 1).   |
| Numerical method             | Newton TRAP     | Maxtrap = 20   | Maxtrap specifies the number of times the trap (bias step) will be repeated in case of divergence (default = 4) |
| Complex Eigen value solver   | index.model     | 1              | Specifies whether the simple refractive index model (INDEX.MODEL = 0) or the complex refractive index (INDEX.MODEL = 1) is used |

Table 2. Parameters used for optical TCAD simulation in Silvaco ATLAS. A detailed glossary is available in the user manual [38].

The device cross-section used for both electrical and optical simulation in TCAD is shown in Figure 8(a), using design parameters listed in Table 1. The AlGaN and GaN regions are created using the statement REGION in the model. To specify the piezoelectric and spontaneous polarization, we use POLARIZATION and CALC.STRAIN in the MODEL statement respectively. POLAR.SCALE is the polarization scale factor (with a default value = 1), whose value is set to 1.1 in order to obtain polarization charge of the order of $\approx 10^{14}\text{cm}^{-2}$. For simulating the complex refractive index, we set the parameter INDEX.MODEL = 1, and numerical analysis is performed using ‘Newton TRAP’ method. We use the PROBE statement to record the effective refractive index at the interface for each simulated gate bias voltage. The real part of the effective refractive index as a function of applied gate voltage is plotted in Figure 9. We observe that the knee point for the real part of the effective refractive is the same as $V_{off}$. We also observe that the 2DEG sheet charge falls to a very negligible value below $V_{off} (-6\text{V})$, which agrees with the C-V simulation reported in section 3.2. The maximum slope of the curve (modulation efficiency) is noticed for $V_g$ in range of $-6\text{V}$ to $-1\text{V}$. The change in effective refractive index obtained from
the TCAD simulation is $\approx -3.6 \times 10^{-4}$ for this voltage range. The change in refractive index is comparable to silicon plasma dispersion modulators [5], and thus the proposed architecture holds great promise for ultra-fast modulation in a practical device realization.

3.4. Simulations of optical mode confinement in ridge wave guide using TCAD simulation in Silvaco ATLAS

Waveguides are an essential and integral part of the electro-optical communication system for on-chip photonic routing of information. Modern fiber-optic communication system typically uses single mode optical fiber as the backbone for light propagation. The single mode condition
for the waveguide structure is indispensable for any integrated opto-electronic device to sustain the fundamental mode of propagation for strong optical confinement and efficient coupling with external optical fibers. A hybrid numerical-analytical design methodology for obtaining single mode condition in ridge waveguides with geometries larger than the wavelength of guided light has been presented in our previous work [40]. We design a ridge waveguide structure following our design methodology and perform TCAD simulation to confirm single mode condition using Silvaco ATLAS. The transverse optical mode is solved using beam propagation method by solving fully vectorial Helmholtz wave equation at zero bias voltage (specified by HELM parameter for the electrodes) [38]. We consider AlGaN cladding layer of total ridge height 4μm and a width of 500nm, and the height of GaN core layer used is 1.3μm. For strong confinement of the light metal electrodes for source and drain contacts are placed 2μm away from the gate. The fundamental TE mode pattern (∂n) of a ridge wave guide structure at wavelength λ = 1.55μm is shown in Figure 10. We have considered larger device dimensions to achieve single mode confinement. However, electrical simulation for larger dimension requires several iterations to converge, and is not performed for this structure. Moreover, mode confinement is not necessary for a free space modulator configuration analyzed in section 3.2.

\[
\frac{\partial N_{2DEG}}{\partial V_g} = \frac{V_{bias} \pm \frac{V_{drive}}{2}}{2} \text{ to ensure low non-linearity.}
\]

In summary, we have presented a concept for an electro-optic modulation scheme leveraging the plasma dispersion effect of the highly confined 2DEG in an AlGaN/GaN heterostructure. A modified Drude model is presented for plasma dispersion effect of the 2DEG and supplemented with Silvaco ATLAS based TCAD simulations. Optical and electrical simulations are performed to optimize the device performance. The device primarily analyzed here is a free space modulator with a structure identical to a III-N HEMT, with additional simulations carried out for a waveguide manifestation of the device, to highlight the versatility of the concept as well as the simulation.
framework demonstrated in this work. The simulated modulation efficiency is on-par with silicon photonic modulators, with the added advantage of high speed of operation and high power handling capacity due to the rich material properties offered by III-V heterostructures.

5. Acknowledgment

The authors thank Prof. Swaroop Ganguly and Prof. Dipankar Saha at IIT Bombay for their valuable inputs on TCAD based simulations, and Dr. Monica Allen and Dr. Jeff Allen at Air Force Research Laboratory, Eglin Air Force Base, Florida for insightful discussions on simulation of heterostructure based modulators. The authors also thank Microelectronics Computation Lab (MCL) at IIT Bombay for providing access to Silvaco ATLAS.

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