ECE 4333-301

Translation of RF GaN HEMT from Nextnano into Silvaco Atlas

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Abstract

This paper discusses the creation of an RF GaN HEMT device in Silvaco Atlas from a reference 1D design in Nextnano and how to extract S-parameters from that device. The covered topics include translation of material parameters across software suites, sensible assumptions on structural design, determining similarity across translations, and appropriate simulation parameters.

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1. Introduction

1.1 Background

For many applications, the High Electron Mobility Transistor (HEMT) is the next evolution of the MOSFET. The planar silicon MOSFET has reached the limit of speed, causing subsequent generations to find clever structural designs to create more rapid transistors. HEMTs offer a solution by having a faster electron mobility (μ) by virtue of being composed of materials with an inherently higher μ. These devices are most relevant in the sphere of high-frequency and high-power applications- telecommunication systems and power systems- not simply because their μ is higher, but because this property is important in many other aspects of transistors. For example, if we take the well-known MOSFET drain current equations, we can see that if all else is equal we will linearly gain current purely by having an increased μ.

$$I_{Dsat} = \frac{1}{2}\frac{W}{L}C_{OX}\mu\left(V_{GS}-V_T\right)^2$$

However, as they are different in both material and structure, they cannot always be simply characterized by MOSFET equations and understandings.

Firstly, HEMTs' semiconductors are inherently n-type, thus p-type doping is especially challenging. Additionally, atop and below their main semiconductor layer (e.g. GaN or GaAs), they have an insulating material (AlN or delta-doped AlGaAs, respectively) that further guides the electrons along the channel semiconductor to increase carrier velocity. Figure 1 illustrates this structure.

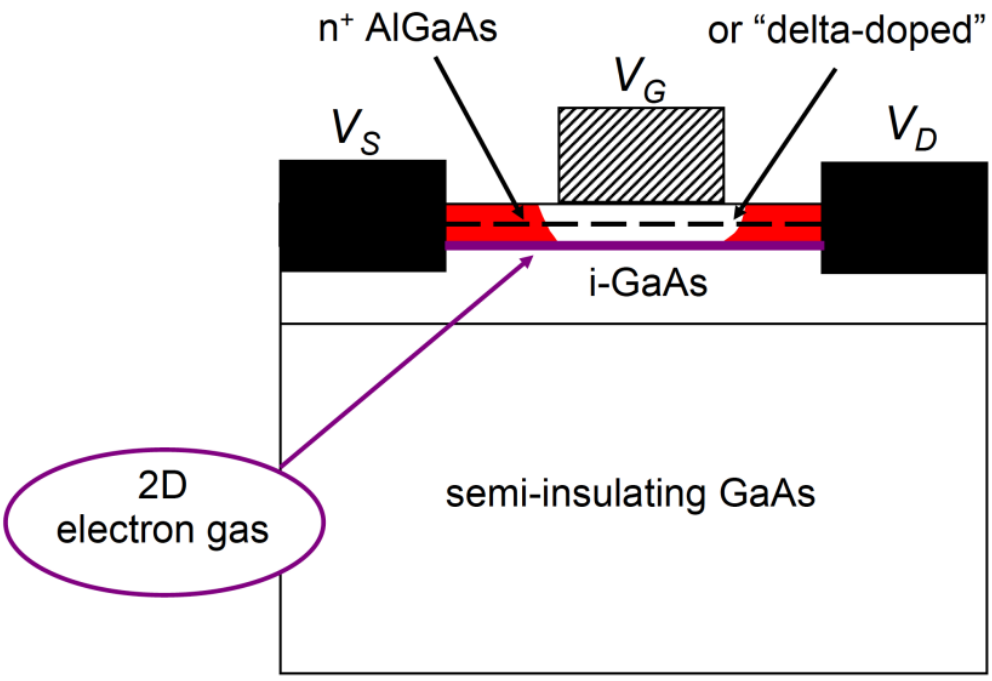


Figure 1: Diagram of an HEMT Device [1].

This structure allows a 2 Dimensional Electron Gas (2DEG) region to form. The product of which is much higher mobility, as within the 2DEG region, electrons can cross the structure with minimal interference. A graphical explanation of this effect is showcased in Figure 2 through the use of an energy band diagram. Energy band diagrams are crucial in understanding many aspects of transistor devices, as they allow us to see the distribution of electrons and holes (and their energies) along the structure. Figure 2 shows this diagram with the x-axis being the depth- as in, the structure from gate towards substrate.

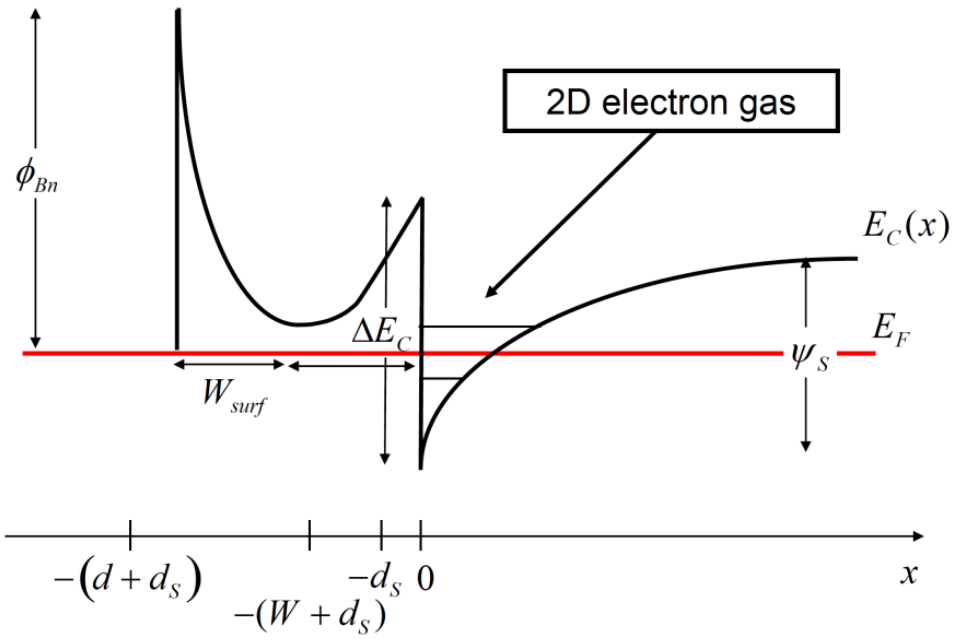


Figure 2: Generic Energy Band Diagram of an HEMT Device in Strong Inversion [1].

The 2DEG region is also often called a “quantum well,” as at this region a significant amount of quantum carriers are present- electrons in this case. The importance of these carriers in the scope of this paper does not go past the fact that they move across the structure more rapidly, so we will not be going into detail about them, however a mention felt appropriate.

1.2 Structure of Paper

The paper will begin with describing the translation of the simulated device from Nextnano to Silvaco Atlas in Section 2, including how to verify whether the device is appropriately translated. Section 3 will describe the simulation methods and some rough results given certain obstacles at the present stage, which will be explained in Section 4. Section 5 will conclude the paper with a summary of the work. In the Appendices, one can find notable pieces of code, project disclaimers, and project progress.

2. Translation of Device

2.1 Material Parameters

An important aspect of these devices, as stated in the introduction, is the materials. Even if we were using default material models in one software, we would need to at least verify that in a different software their parameters are equal. However, in our Nextnano simulation, the materials of GaN and AlN are heavily modified, so it is to be assumed that modifications are necessary in Silvaco Atlas as well.

Table A in Appendix A.1 shows the material defaults of GaN and AlN in Atlas, and Figure 9 in the same appendix shows the material modifications of the two materials in Nextnano. Of importance is to read the commented portions of the Nextnano to the far right of the page, as those roughly match the Syntax column of Table A to the Nextnano parameters. Some of the more important parameters are the direct band gap, the electron effective masses, and the hole effective masses.

To set material parameters in Atlas, one simply calls the "MATERIAL" statement, declares the material to be modified, and adjusts the material per the "Syntax" column. For example, if we wanted GaN to have a bandgap of 3.51 eV, we write the following:

```
MATERIAL MATERIAL=GaN EG300=3.51
```

Some parameters and their syntax in Atlas are not obviously stated in the manual, for example the dielectric constants of these materials (which turns out to be "PERMITTIVITY") [2]. An easy way to check the total material parameters is to include the statement "MODEL PRINT" in the Atlas input file. This will at least give insight into the values of these parameters. To find the syntax, one needs to reach the last chapter of any Atlas manual- titled "Statements"- and shift through the "MATERIAL" statement's parameters until the desired parameter is found. Using these tools help with other materials which do not have in-depth tables- in our case, AlGaN.

Both in Nextnano and Atlas, the material parameters of AlGaN are calculated based on the parameters of GaN & AlN and the x composition of the material. The x composition is the ratio of aluminum to gallium- $Al_xGa_{1-x}N$. The Atlas defaults are 0.30; based on Nextnano we desire the x composition to be 0.45. From there, we could let Atlas determine the rest of the material parameters for us. However, there is a slight discrepancy between what Nextnano calculates the AlGaN parameters to be and what Atlas calculates, even though they are supposed to be fully determined by the GaN and AlN parameters that have been set. Therefore, the best course of action is to find the material parameter file outputted by Nextnano and transfer those values to Atlas explicitly. For easier readability, the Nextnano++ version of the output file is provided in Appendix A.1 as Figure 10 (the input file is written in the Nextnano^3 syntax, hence the differentiation).

The last material to mention is silicon carbide, which is the substrate of the device. This also required modification, even though in Nextnano SiC is left as-is. Most notably, the bandgaps differ between the two programs, Nextnano calling for 6.0 eV and Atlas calling for 2.9 eV.

One crucial parameter that does not get mentioned in the Atlas tables or the Nextnano input file is electron affinity, denoted as χ. This is the energy difference between the vacuum level and the conduction band. Manually setting χ of materials is not quite straight-forward. In Atlas, there are two ways to set a material's χ: through explicit instruction (with the "AFFINITY" parameter) or the "ALIGN" parameter. The ALIGN parameter is far more useful when we do not know χ directly, as the calculations are done

with respect to the material with the smallest bandgap and the conduction band discontinuities. That is, the sudden jumps the conduction band makes since each material in the device creates a heterojunction (a junction between two materials with different band gaps). To align a material that is immediately neighboring the reference material- GaN in our case- one must use this equation:

$$A = \frac{\Delta E_C}{E_{g2} - E_{g1}} = \frac{\Delta E_C}{\Delta E_{g21}} \quad (1)\ [2]$$

Where E_{g1} is the reference material, E_{g2} is the material to be aligned, and ΔE_C is the conduction band discontinuity between the two materials. For a material that is not immediately neighboring the reference material, the following formula is used:

$$A = \frac{\Delta E_{g32}}{\Delta E_{g31}} \frac{\Delta E_{C32}}{\Delta E_{g32}} \quad (2)\ [2]$$

As an example, if we have a GaN region with a bandgap of 3.51 eV as declared above, and we want to align a region of AlN followed by a region of AlGaN with bandgaps of 6.25 eV and 4.66 eV respectively, we would use Equation 1 to solve for AlN's alignment and Equation 2 for AlGaN. To find ΔE_C, in this case, we can use the energy band diagrams generated from our prior Nextnano sim, as seen in Figure 3. In this diagram, from left to right, the materials are: a metal, AlGaN, AlN, and GaN. By inspection of the graph, we can deduce that the ΔE_C between GaN & AlN is about 1.92 eV and between AlN & AlGaN is about 1.07 eV. Also note that the Schottky barrier height (the conduction band discontinuity between the metal and the AlGaN region) is precisely 1 eV.

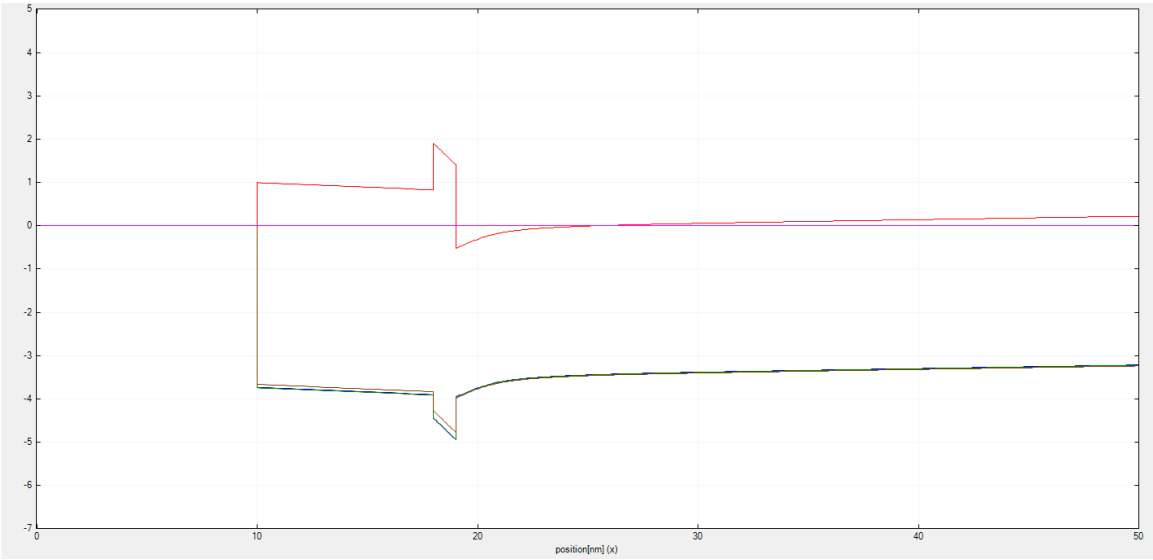


Figure 3: Energy Band Diagram of GaN HEMT Generated by Nextnano. Gate Bias is at 0 V

Plugging these values into the equations above, we get that to align AlN, the *A* value is 0.7, and to align AlGaN it is about 0.94. That means that 70% and 94%, respectively, of the band discontinuity will be on the conduction side. We can see that this looks about right as the valence band discontinuity (ΔE_V) accounts for a third of the discontinuity between the GaN and AlN regions and nearly none between the GaN and the AlGaN regions.

To set the metal work function (W_M), simply add 1 eV to the χ that will result onto the AlGaN region. If, for example, χ is 1.5 eV, W_M will be 2.5 eV. Thus, include this statement in the simulation file:

```
contact name=gate workfunction=2.5
```

The results of this process can be found in Appendix A.1, Figure 11. Note that some parameters are not adjusted (such as the lattice constants of GaN and AlN) since there are some parameters that are identical between programs. Also, the SiC parameters are lacking as Nextnano does not provide as in-depth parameters at output for that material.

2.2 Structure Specifications

The structure has two components in both Nextnano and Atlas and is thus one of the more straight-forward portions of the project. Both have a mesh and a definition of regions. The main difference is in the fact that our Nextnano simulation is monodimensional- from gate to substrate- whereas in Atlas we also need the drain and source contacts, so a bidimensional structure is necessary.

The mesh is simply the resolution of the structure to be calculated. Both are split into comparable units of spacing (Atlas) and nodes (Nextnano), where each refers to the distance between each meshline. Because our region of interest is in the GaN region, we set the mesh along that region to have a high resolution; everywhere else can have a relatively low resolution. For example, to set a mesh of 100 nm wide and 50 nm deep with a resolution of 100x50, one may write:

```
x.mesh loc=0.000 spac=0.001

x.mesh loc=0.100 spac=0.001

y.mesh loc=0.000 spac=0.001

y.mesh loc=0.050 spac=0.001
```

It is important to note that whereas Nextnano's nodes are a fixed distance apart within a certain region, if two neighboring meshes have different spacing in Atlas then there will be a gradient towards the next mesh region. For example, if one writes the same example as above, but changes the y mesh spacing as so:

```
y.mesh loc=0.000 spac=0.001

y.mesh loc=0.050 spac=0.005
```

Then the mesh of the structure will seem as it does in Figure 4:

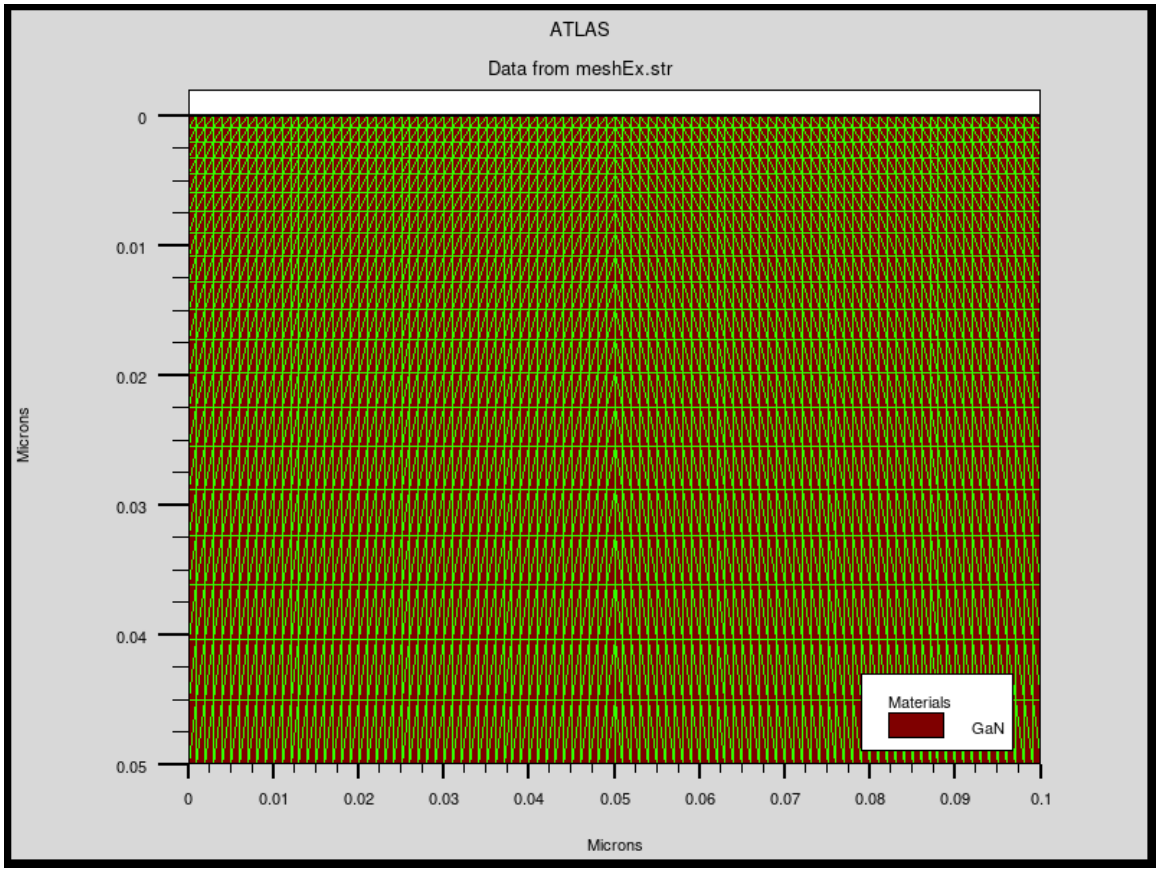


Figure 4: Variable Mesh of a Monolithic Structure

As per the region definitions, those essentially specify what material goes where. Usually, one matches the mesh boundaries with the various regions. Additionally on Atlas, one can set where electrodes and contacts are and their characteristics- though those fall under their own statements of "ELEC" and "CONTACT", the latter of which is seen in the previous section. For brevity, refer to Appendix A.2, Figures 12 and 13 for detailed definitions of both the meshes and regions for both programs. Figure 5 shows the final structure designed in Atlas. Note that the AlN layer above the GaN layer is not visible as it is just 1 nm deep, whereas the rest of the structure is 1 micron deep.

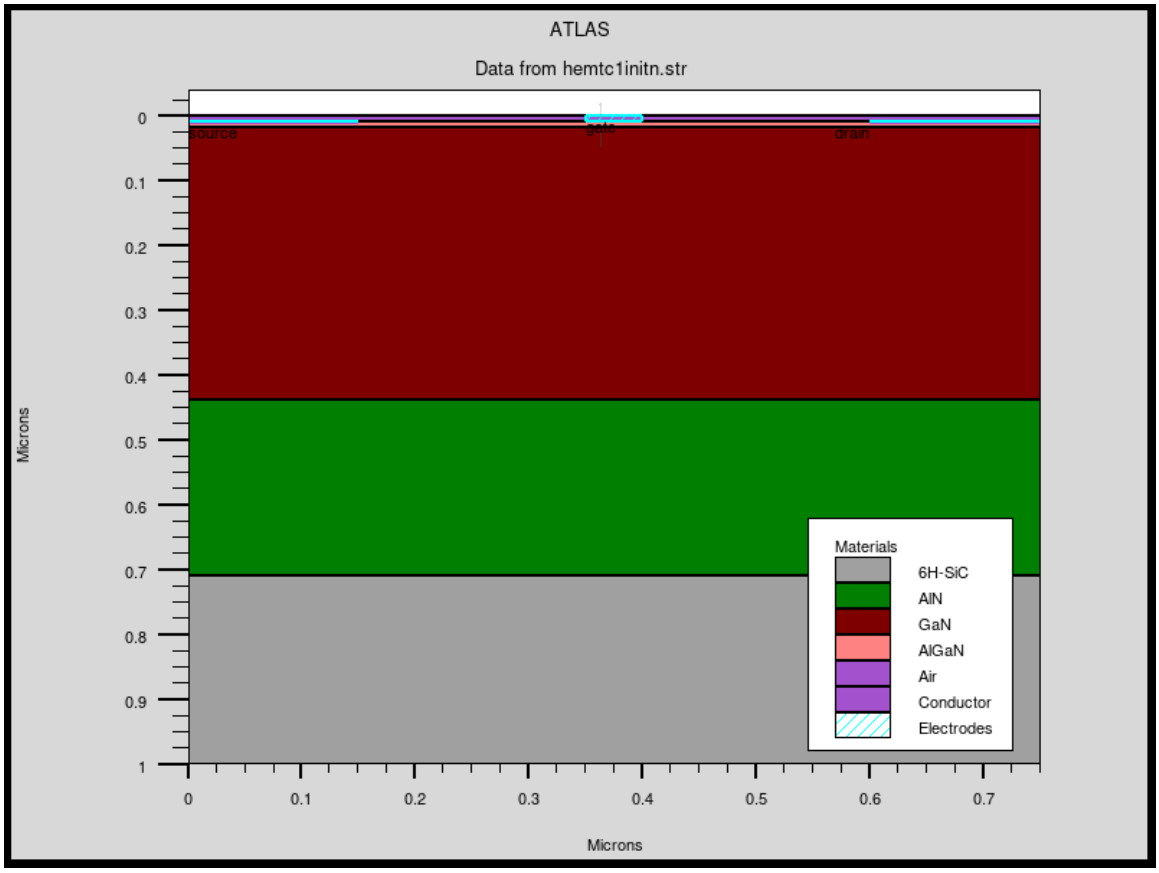


Figure 5: GaN HEMT Structure

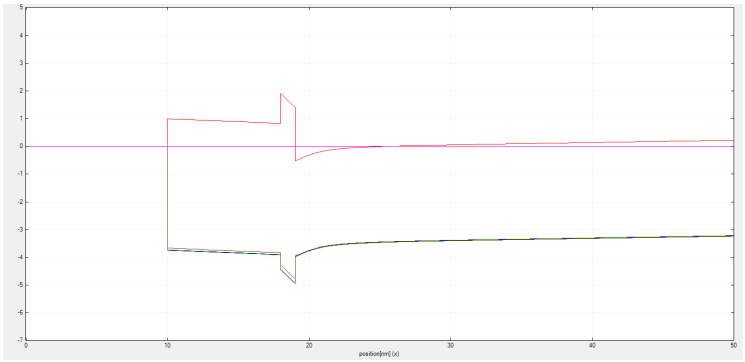
The placement and size of the electrodes is a topic which requires some amount of personal judgment, as the Nextnano simulator does not include them in its definitions, and the physical structures are not clearly defined. For the gate electrode, the conclusion is to overlay it onto the metal layer. As per the drain and source electrodes, there are a few choices. One could simply place them above the metal layer, however some HEMT schematics show the electrodes in the structure. For the latter option, one must make sure that the electrodes reach a depth well below the quantum well region. [3] Conventional MOSFET design has the general rule-of-thumb of having the junctions reach 30% of the

channel layer's depth [4]. As seen in Figure 5, the first option was chosen- as some unpublished literature on this specific transistor showed this to be the case [5].

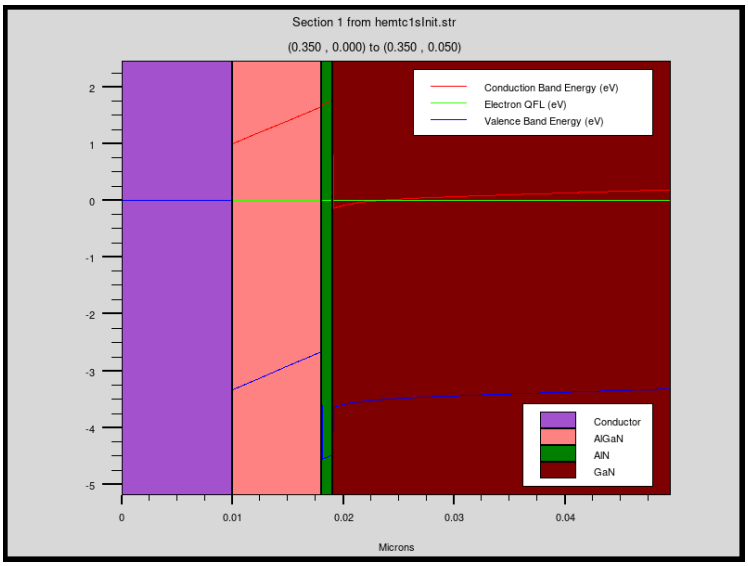
2.3 Verification Methodology

To verify the translation from Nextnano to Atlas, we can find many answers in if the energy band diagrams match. To generate an energy band diagram in Atlas, one simply needs to open the solved structure in Silvaco's plotting program Tonyplot, make a cutline through the region of interest, and select the desired band parameters. In the following figures, the cutline will be made through the center of the structure along the x axis and 50 nm deep.

As an example, Figure 6 shows the energy band diagrams generated by Nextnano and Atlas at 0 V gate bias. These band diagrams have a slight difference in how much the GaN region bends down, limiting the amount of 2DEG. Additionally, the AlN and AlGaN regions do not have the appropriate shape.



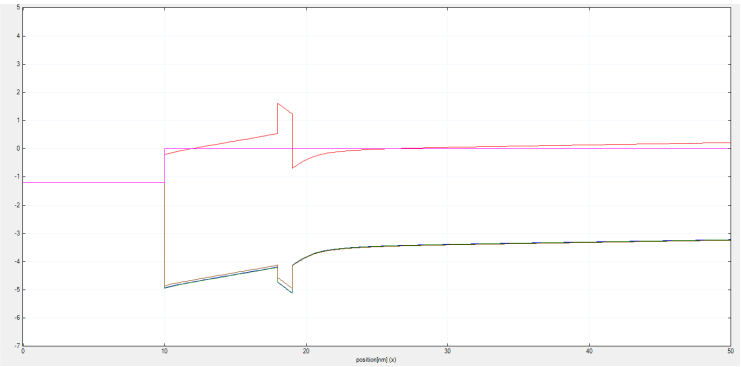
a.



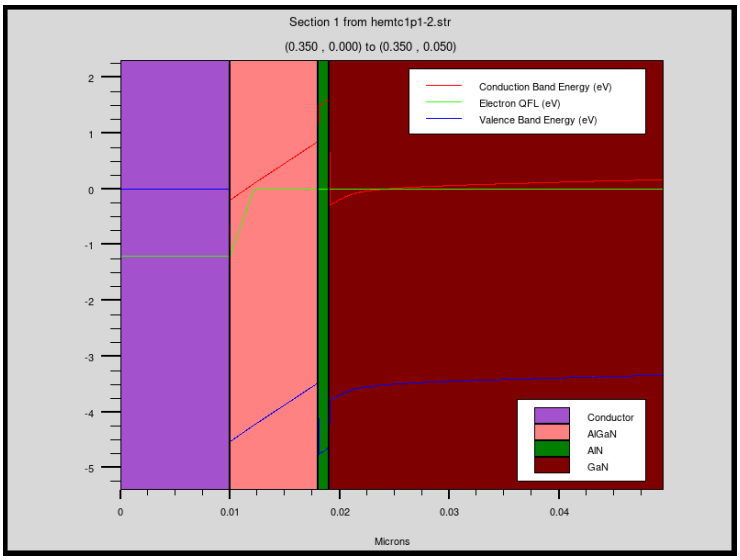
b.

Figure 6: Comparison of Nextnano (a.) and Atlas (b.) Devices at 0 V Gate Bias

Similarly, at 1.2 V gate bias per Figure 7, the energy band diagrams have some similarity in the GaN region, and the AlGaN region seems to behave better, however they differ significantly in the AlN layer.



a.



b.

Figure 7: Comparison of Nextnano (a.) and Atlas (b.) Devices at 1.2 V Gate Bias

Note that these Atlas results are of a recent, but not current, version of the code. The most up-to-date code, as seen in the Appendices, produces results that improve some aspects of the energy band diagrams in terms of objective accuracy. However, these energy band diagrams were more functionally accurate, hence their usage for this point.

3. Simulation

There are two simulation types done in this project: DC solutions for the energy band diagrams shown in the previous section, and AC analysis for the S-parameters this project aims to extract. The physics/simulation models used are the Schrodinger-Poisson models of Atlas (which match those of Nextnano). One of the parameters needed are the amount of eigenvalues, which essentially controls the precision of the simulation. Another is the type of carriers. In this case both electrons and holes are suitable for the model. [2] Hole and valence band calculations are not quite so important in the scope of this research, however they also do not pose any problems to be present. [3]

The simplest way to simulate and store DC simulations is to write the following statements:

```
solve vgate=1.2


save outf=example.str
```

In this case, the gate will receive a bias voltage of 1.2 V and any other electrodes will remain at 0 V. If the next statement specifies a different electrode's bias, the gate bias will remain at 1.2 V for that measurement.

For AC analysis, a similar method can be used. However, to simulate at more than just one frequency a combination of log and set files are used. Log files catalog the simulations that occur since their declaration and set files specify the graphing of the results. As an example, the AC analysis has the following code written:

```
log outf=example.log master gains s.params inport=gate outport=drain width=50

solve ac freq=1e9 fstep=1e9 nfstep=10

solve ac freq=2e10 fstep=1e10 nfstep=5

tonyplot example.log -set example1.set
```

The S11, S22, S12, and S21 results of this simulation are as in Figure 8. Besides the inaccuracies of the structure, the output is still about what one could expect from these devices. [6] Though DC bias should have some effect on these characteristics, no real change in the output was realized by any sensible bias point. Hence, these simulations were run at 0 V bias at all ports.

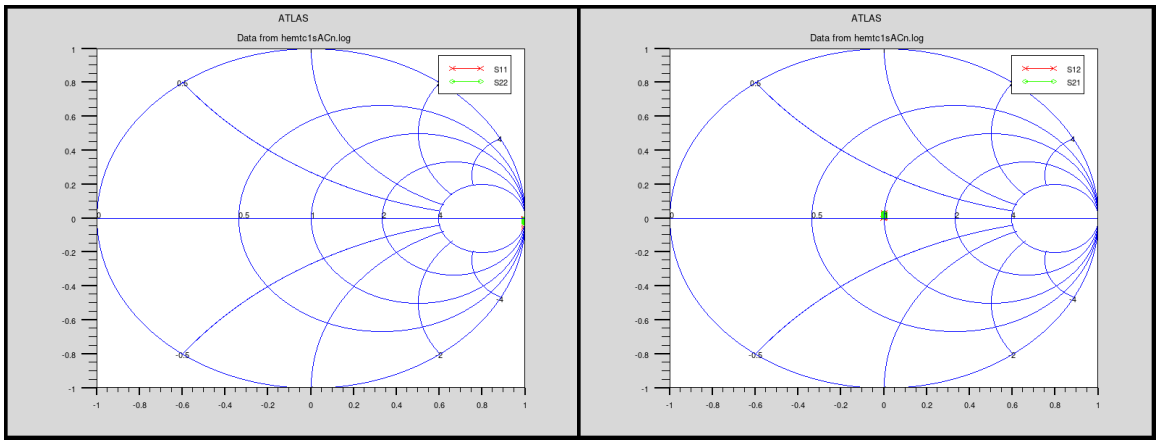


Figure 8: S-parameter Simulation Output

4. Present Issues

Suitable matching between the Atlas and Nextnano structures has not been realized. Explicit definitions assist in allowing for the band structures to have a decent relative behavior, however at the same bias the entire structures are considerably offset.

The most accurate structure, definition-wise, does not exhibit anywhere near the appropriate energy band diagram characteristics, and the most accurate structure energy band diagram-wise does not exhibit appropriate RF characteristics. The reason for all of these mismatches has not been found, and one could suppose it may be some minor detail in the depths of the Atlas simulator. This is the conclusion as all possibilities in adjusting material parameters and simulation methods and models have been exhausted. Some tactics attempted have been to use entirely default parameters, omit the AlN barrier layer, simply modify Atlas example files, and try radically different structural architectures, all to no avail.

5. Conclusion

The usage of various simulators is important to view certain devices from multiple angles, especially as different tools specialize in different aspects of the same subject. Importantly, they not only provide different data, but they can even present the same data in different ways, allowing for new and helpful relationships to be concluded. Therefore, deeper understanding of multiple software suites is paramount to simulating devices effectively.

Appendix A

A.1 Material Parameters

Table A: Electronic Band-Structure and Polarization Parameters for InN, GaN and AlN [2]

Parameter	Symbol	Syntax	Units	InN	GaN	AlN
Electron eff. mass (z)	m_{cz}	MZZ	m_0	0.11	0.20	0.33
Electron eff. mass (t)	m_{ct}	MTT	m_0	0.11	0.18	0.25
Hole eff. mass param.	A1	A1		-9.24	-7.24	-3.95
Hole eff. mass param.	A2	A2		-0.6	-0.51	-0.27
Hole eff. mass param.	A3	A3		8.68	6.73	3.68
Hole eff. mass param.	A4	A4		-4.34	-3.36	-1.84
Hole eff. mass param.	A5	A5		-4.32	-3.35	-1.92
Hole eff. mass param.	A6	A6		-6.08	-4.72	-2.91
Valence band reference	Ev0		eV	-1.59	-2.64	-3.44
Direct band gap (300K)	Eg(300)		eV	1.89	3.42	6.28
Spin-orbit split energy	D1	DELTA1	eV	0.041	0.019	-0.164

Crystal-field split energy	D2	DELTA2	eV	0.0013	0.01413	0.01913
Lattice constant	a_0	ALATTICE	Å	3.548	3.189	3.112
Elastic constant	C33	C33	GPa	200	392	382
Elastic constant	C13	C13	GPa	94	100	127
Hydrostatic deformation potential	ac	AC	eV	-4.08	-4.08	-4.08
Shear deform. potential	D1	D1	eV	-0.89	-0.89	-0.89
Shear deform. potential	D2	D2	eV	4.27	4.27	4.27
Shear deform. potential	D3	D3	eV	5.18	5.18	5.18
Shear deform. potential	D4	D4	eV	-2.59	-2.59	-2.59
Spontaneous polarization	P_{sp}	PSP	C/m^2	-0.04	-0.03	-0.09
Piezoelectric const. (z)	e_{33}	E33	C/m^2	0.81	0.67	1.5
Piezoelectric const. (x,y)	e_{31}	E31	C/m^2	-0.41	-0.34	-0.53

Figure 9: Nextnano Material Modifications of GaN and AlN

```
binary_wz{
    name = "Al(x)Ga(1-x)N,x=0.450,1-x=0.550"
    valence = "(unknown)"
    lattice_consts{
        a =      3.15435
        a_expansion =      0.00000
        c =      5.09365
        c_expansion =      0.00000
    }
    dielectric_consts{
        static_a =      9.00550
        static_c =      9.41150
        optical_a =      5.01550
        optical_c =      5.01550
    }
    elastic_consts{
        c11 =      392.700
        c12 =      141.400
        c13 =      106.900
        c33 =      386.750
        c44 =      109.950
    }
    piezoelectric_consts{
        e31 =     -0.417500
        e33 =      1.50400
        e15 =     -0.381000
    }
    pyroelectric_consts{
        p1 =     -0.540025E-01
    }
    conduction_bands{
        Gamma{
            mass_l =     0.257300
            mass_t =     0.246100
            bandgap =      4.66183
            bandgap_alpha =      0.00000
            bandgap_beta =      0.00000
            defpot_absolute_l =     -13.9550
            defpot_absolute_t =     -5.49500
        }
    }
    valence_bands{
        bandoffset =     -1.08600
        defpotentials = [     -9.73000      ,      6.03000      ,      8.47000     ,     -4.01000     ,     -3.73000     ,     -4.55500     ]
        delta = [     -0.705500E-01 ,     0.596700E-02 ,     0.596700E-02 ]
        HH{
            mass_l =      2.19350
            mass_t =      5.56900
        }
        LH{
            mass_l =      2.19350
            mass_t =     0.190500
        }
        SO{
            mass_l =     0.195000
            mass_t =      2.31950
        }
    }
    kp_6_bands{
        A1 =     -5.70250
        A2 =     -0.354500
        A3 =      5.28500
        A4 =     -2.49700
        A5 =     -2.53150
        A6 =     -3.43300
    }
    kp_8_bands{
        S1 =     0.838550
        S2 =     0.984950
        E_P1 =       14.2250
        E_P2 =       14.2250
        B1 =     0.515350E-01
        B2 =     0.515350E-01
        B3 =     0.515350E-01
        A1 =     -2.46455
        A2 =     -0.354500
        A3 =      2.04705
        A4 =     -0.878300
        A5 =     -0.912800
        A6 =      1.05065
    }
}

```

Figure 10: Nextnano AlGaN Material Definition

```
# MATERIAL PARAMS
# GaN mod - order based on Atlas manual
MATERIAL MATERIAL=GaN MZZ=0.206 MTT=0.202 A1=-7.21 A2=-0.44 A3=6.68 A4=-3.46 A5=-3.40 A6=-4.90 \
                      EG300=3.51 DELTA1=0.010 DELTA2=0.00567 C33=398 C13=106 AC=-6.8 \
                      D1=-3.7 D2=4.5 D3=8.2 D4=-4.1 E33=1.27 E31=-0.034
#MATERIAL MATERIAL=GaN PERMITTIVITY=9.28

# AlN mod - order based on Atlas manual
MATERIAL MATERIAL=AlN MZZ=0.32 MTT=0.30 A1=-3.86 A2=-0.25 A3=3.58 A4=-1.32 A5=-1.47 A6=-1.64 \
                      EG300=6.25 DELTA1=-0.169 DELTA2=0.00633 C33=373 C13=108 AC=-3.9 \
                      D1=-17.1 D2=7.9 D3=8.8 D4=-3.9 E33=1.79 E31=-0.50
MATERIAL MATERIAL=AlN ALIGN=0.7024777372
#MATERIAL MATERIAL=AlN PERMITTIVITY=8.67

#SiC mod - Order based on nn++ material params. list
MATERIAL MATERIAL=SiC-6H ALATTICE=4.3596 PERMITTIVITY=9.72 C11=290 C12=235 MC=0.68 \
                         EG300=6.0
MATERIAL MATERIAL=SiC-6H ALIGN=0.5426787149

# AlGaN mod - order matches GaN and AlN + explicitly stating certain parameters
MATERIAL MATERIAL=AlGaN MZZ=0.2573 MTT=0.2461 A1=-5.7025 A2=-0.3545 A3=5.285 A4=-2.497 \
      A5=-2.5315 A6=-3.433 DELTA1=-0.07055 DELTA2=-0.005967 C33=386.75 \
      C13=106.9 EG300=4.66 AC=-5.495 D1=-9.73 D2=6.03 D3=8.47 D4=-4.01 \
      E33=1.504 E31=-0.4175 ALATTICE=3.15435
MATERIAL MATERIAL=AlGaN ALIGN=0.9350469565
#MATERIAL MATERIAL=AlGaN PERMITTIVITY=9.0055
```

Figure 11: Material Modifications in Silvaco Atlas

A.2 Structural Specifications

```
$regions                                                                    !

 !-------------------------------------------------------------------------------
 ! These are the regions of the AlGaN/GaN region (without surface or GaN cap layer).
 !-------------------------------------------------------------------------------
 region-number = 1    base-geometry = line   region-priority = 1           !
 x-coordinates = 0d0  10d0

 region-number = 2    base-geometry = line   region-priority = 1           !
 x-coordinates = 10d0 18d0

 region-number = 3    base-geometry = line   region-priority = 1           !
 x-coordinates = 18d0 19d0

 region-number = 4    base-geometry = line   region-priority = 1           !
 x-coordinates = 19d0  439d0


 !-------------------------------------------------------------------------------------
 ! These are the regions left of the AlGaN/GaN region, i.e. the GaN cap and the surface.
 !-------------------------------------------------------------------------------------
 region-number = 5    base-geometry = line   region-priority = 1           !
 x-coordinates = 439d0   709d0                                            ! air

 region-number = 6    base-geometry = line   region-priority = 1           !
 x-coordinates = 709d0   1000d0

$end_regions                                                               !
!-------------------------------------------------------------------------!

!-------------------------------------------------------------------------!
! For every boundary between regions, there has to exist a grid line. And  !
! between these grid lines there are a certain number of nodes which       !
! determine the resolution of the simulated region. In order to specify    !
! inhomogeneous grids you can use a grid factor different from one. This   !
! means that the distance between each node is increased by this factor    !
! from i to i+1.                                                           !
!-------------------------------------------------------------------------!
$grid-specification                                                        !
 grid-type       =    1 0 0                                               !
 x-grid-lines    =  0d0 10d0  18d0 19d0 439d0 709d0 1000d0
 x-nodes         =       5   25  15   1050    50  20                      ! originally: [blank] 5   25  15   10500  50  20
 x-grid-factors  =       1d0 1d0 1d0 1d0 1d0  1d0
$end_grid-specification                                                    !
!-------------------------------------------------------------------------!
```

Figure 12: Nextnano Region and Grid Specifications

```
mesh

x.mesh loc=-50    spac=.5
#x.mesh loc=0.15   spac=0.05
#x.mesh loc=0.60   spac=0.05
x.mesh loc=50   spac=.5

y.mesh loc=0.000  spac=0.002
y.mesh loc=0.010  spac=0.002
y.mesh loc=0.018  spac=0.003
y.mesh loc=0.019  spac=0.0001
y.mesh loc=0.439  spac=0.010
y.mesh loc=0.709  spac=0.010
y.mesh loc=1.000  spac=0.010

# STRUCTURE SPEC

region  num=1  material=SiC-6H y.min=0.709  y.max=1.000
region  num=2  material=AlN    y.min=0.439  y.max=0.709
region  num=3  material=GaN    y.min=0.019  y.max=0.439 \
               qwell  well.nx=10500  well.ny=5
region  num=4  material=AlN    y.min=0.018  y.max=0.019
region  num=5  material=AlGaN  y.min=0.010  y.max=0.018  x.comp=0.45
region  num=6  material=Air    y.min=0.000  y.max=0.010

elec    num=1  name=source  x.min=-50 x.max=-27.5 y.min=0.000  y.max=0.010
elec    num=2  name=gate    x.min=-22.5 x.max=22.5 y.min=0.000  y.max=0.010
elec    num=3  name=drain   x.min=27.5 x.max=50 y.min=0.000  y.max=0.010

contact name=gate workfun=4.23
```

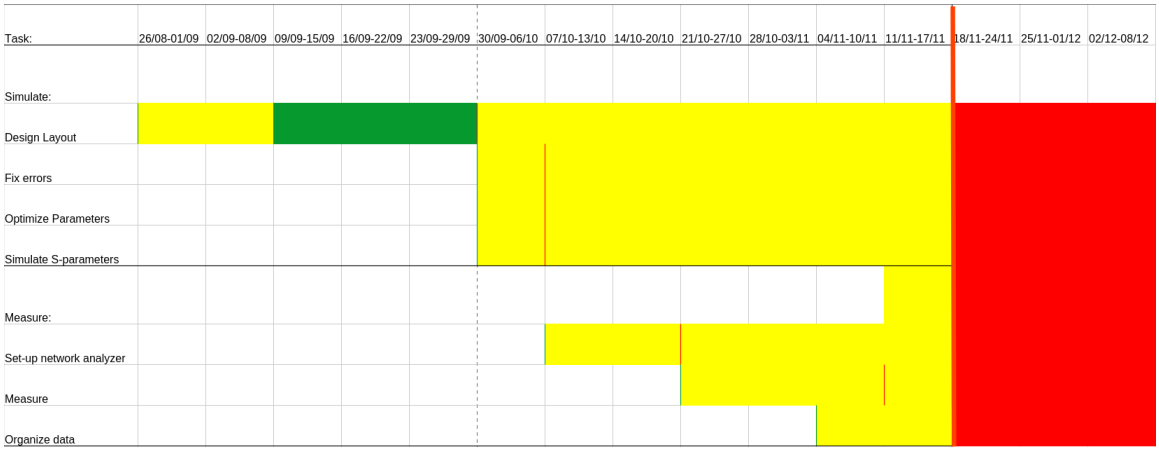
Figure 13: Atlas Region and Mesh Specifications

Appendix B

B.1 Safety, Environmental, and Social Impacts Disclaimer

Due to the nature of this project, especially up to this point, there are no reportable safety, environmental, or social considerations. All of the work until now is done virtually, and any future lab work will be with low-voltage lab equipment on an wafer that is already fabricated.

B.2 Gantt Chart



B.3 Budget Chart

Week	Hours	Cost
26/08-01/09	2	30
02/09-08/09	6	90
09/09-15/09	6	90
16/09-22/09	6	90
23/09-29/09	12	180
30/09-06/10	2	30
07/10-13/10	14	210
14/10-20/10	18	270
21/10-27/10	8	120
28/10-03/11	8	120
04/11-10/11	8	120
11/11-17/11	8	120
18/11-24/11	4	60
Totals:	102	1530

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3. Kim, TW Ph.D. Personal Interviews, September-November 2024.

4. Stephen A. Campbell, Fabrication Engineering at the Micro- and Nanoscale, Oxford University Press, New York, NY, pp. 132, 2013.

5. S. Chakraborty, W. Amir et al. "Addressing Reliability Issues in AlGaN/GaN HEMTs: State-of-the-Art Developments and Future Prospects". University of Ulsan, *not yet published*.

6. L. Dunleavy, "Model-Based GaN PA Design Basics: GaN Transistor S-Parameters, Linear Stability Analysis and Resistive Stabilization," Qorvo Inc., 28 August 2019.