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**A NOVEL APPROACH TO MODELING TUNNEL  
JUNCTION DIODES USING SILVACO ATLAS  
SOFTWARE**

by

Robert Gelinas

December 2005

Thesis Advisor:

Sherif Michael

Second Reader:

Todd Weatherford

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SILVACO ATLAS**

Robert J. Gelinas  
Lieutenant, United States Navy  
B.S.E.E, Virginia Military Institute, 1998

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**NAVAL POSTGRADUATE SCHOOL  
December 2005**

Author: Robert J. Gelinas

Approved by: Sherif Michael  
Thesis Advisor

Todd Weatherford  
Second Reader

Jeff Knorr  
Chairman, Department of Electrical and Computer Engineering

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## **ABSTRACT**

This thesis investigates the ability to model a tunnel junction device using the ATLAS device simulator by Silvaco International. The tunnel junction is a critical component of a multijunction solar cell. This thesis will concentrate on simulating the tunnel junction for application as part of a multijunction solar cell. It will try several methods, in ATLAS device simulator, to produce a model of the tunnel junction that can later be used while designing multijunction devices. These methods will consist of the review of past work, attempting to modify past work to be applied in the current design, producing a new tunnel junction simulation from the ground-up, and review of the simulations of similar devices to learn if they can be modified and applied to making a working tunnel junction model.

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## **EXECUTIVE SUMMARY**

Currently the methods for designing and testing solar cells are long and costly. By doing more of the designing and testing of solar cells using computer simulation tools, designers will be able to reduce the amount of time and money spent on the design process. Also by designing and simulating the cell in a virtual environment the designer will be able to better optimize the cell for enhanced performance. By improving the performance of new cells, systems that derive their power from solar cells will become more powerful and more useful. These systems are of high importance to the United States' national goals and to the Department of Defense's goal of a smaller, lighter, and more capable fighting force. Current and future products requiring more efficient solar power include but are not limited to; portable battery chargers for long range patrols, solar powered communication devices, solar powered UAVs and more powerful and capable satellites. The latter meet the Commander in Chief's goal of continued space exploration with future manned missions to the Moon and Mars.

Research has been performed at Naval Postgraduate School investigated the use of Silvaco International's powerful device simulator ATLAS to create virtual models of multijunction solar cell devices. This research not only involved simulating the solar cell but also optimizing of the cell. This allows a cell to be tailor designed for the application for which it will be used. One problem that the research has not been able to effectively solve is the simulation of the tunnel junction that connects the different layers of a multijunction cell.

The tunnel junction in a multijunction solar cell is a critical component and producing a working model of it is very important. This research investigated several methods, in ATLAS device simulator, to produce a model of the tunnel junction for designing multijunction devices. The first method uses a review of past work and an attempt to make previous simulations work on current versions of ATLAS software. The second method was to design a new tunnel junction simulation from the ground-up in hopes of making a working model. The last method was a review of the simulations of

similar devices to determine if they could be modified and applied to making a working tunnel junction device. The thesis includes background on tunnel junctions, a review of simulations done in prior work, and original simulations performed for this thesis. All coding used for ATLAS will be included in the Appendices.



## I. INTRODUCTION

The tunnel diode was first discovered in 1958 by Leo Esaki while doing research for his doctoral dissertation [Ref. 17]. He was doing research into the properties of heavily doped pn junction when he discovered that these pn junctions, at low forward and reverse bias, conduct electricity via the tunneling phenomena. By the 1960 Solid-State Circuits Conference the Esaki junctions had shown so much promise for their ability to operate at low power and with unmatched speed that 10 of the 43 technical papers presented at that conference were studies involving this junction [Ref. 17]. As more research was performed some limitations of the device were found and with the arrival of the integrated circuit the research in this field went in a different direction. Today one of the uses of the tunnel diode is in advanced multijunction solar cells.

The purpose of this thesis is to effectively model the tunnel junction diode using Silvaco's ATLAS software. In recent years a lot of research at Naval Postgraduate School has been performed on how to effectively model, simulate and optimize complex multijunction solar cells using Silvaco's ATLAS software. By accomplishing this task researchers and designers would be able to produce more efficient cells at less expensive prices. This would allow more power generation for the same area and weight of solar cells. By lowering the cost of producing these cells and increasing the overall performance, companies will be able to produce cheaper more powerful solar power devices. The primary use of these power devices will be in producing more capable satellites.

One of the keys to making an effective model of a solar cell is to be able to model all components of the cell. The complex multijunction cells consist of layers made of different materials to optimize the power produced. The tunnel junction is used to connect these layers while ensuring that significant power is not lost in the junction. Silvaco's ATLAS is a powerful device simulator that has been used by P. Michalopoulos [Ref. 12], M. Green [Ref. 15], and A. Bates [Ref. 14] to simulate solar cell devices. Their work proved the value of Silvaco's software to a designer and have

spawned continued research into this area. The most recent research of A. Bates [Ref. 14] and M. Green [Ref. 15] was not successful in simulating the tunnel junction between the layers of the device.

In this thesis the sole objective is to design a working ATLAS model of a tunnel junction that can be used in further research being done into optimizing and modeling solar cells. Chapter II will cover the background physics on semiconductors, pn junctions, solar cells and tunnel junction devices. Chapter III will investigate Silvaco International's ATLAS device simulator and how it can be used to simulate a tunnel junction device. Chapter IV will cover simulation models that were used and the results that were obtained during these simulations. Lastly Chapter V will give conclusions and recommendations. The Appendix has copies of the ATLAS Deckbuid code that is used during the thesis and the Runtime Output files from ATLAS.

## II. BACKGROUND

This thesis examines a novel process to simulate p-n tunnel junctions that are used to connect different layers of multi-junctions solar cells. This chapter is going to give the basic background information on semiconductor physics, tunnel junctions and how a tunnel junction is used in a multi-junction solar cell.

### A. SEMICONDUCTOR PHYSICS

When discussing basic electrical properties, materials can be broken into three basic categories; insulator, conductor and semiconductor. Semiconductors are the most intriguing type of material and have lead the way for the many of the advancements of technology in society. The most basic intrinsic semiconductor is silicon and it will be used to demonstrate basic semiconductor physics and operation.

#### 1. Silicon Crystal Structure

The Periodic Table shows that Silicon (Si) is a Group IV element. By being a Group IV element when isolated it has 4 electrons in its outer most shell [Ref. 3].

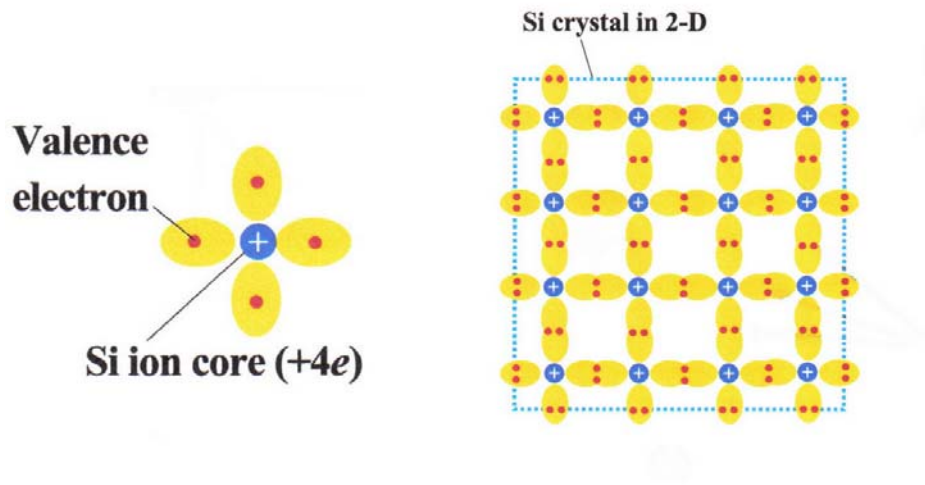


Figure 1. A simple diagram of an isolated Si atom and Si crystal structure [After Ref. 3].

These electrons are called valence electrons and when perfect pure Silicon crystal structure occurs these electrons are shared between atoms next to each other producing a bonded diamond structure. This bonded pure intrinsic Silicon is an ideal structure at zero Kelvin with no impurities or crystal defects. To understand what happens when temperature increases or impurities are added knowledge of band theory is required.

## 2. Energy Band Theory

Energy band theory is an important concept in explaining how electrons react to different conditions within a crystal structure. The spread of energies of electrons can be described by a set of allowed states that are called energy bands [Ref. 4]. These energy bands consist of a lower band of energy states called the valence band, an upper band of energy states called the conduction band and the energy gap between these states, which is called the bandgap [Ref. 4]. Electrons must either exist in the Conduction Band or the Valence Band. Different elements have different value bandgaps and these different bandgaps greatly affect these element's electrical properties. The Fermi level ( $E_F$ ) is also used in the band diagram and it denotes the average energy level for electrons. In an intrinsic semiconductor  $E_F$  is usually placed in the center of the bandgap. Elements with larger bandgaps are insulators, with no bandgaps or negative band gaps are conductors and semiconductors fall in between the two [Ref. 4]. For a material to conduct electricity it must have electrons in the conduction band or holes in the valence band. Electrons naturally gravitate towards lower energy levels and when an element is at zero Kelvin the valence band is completely full of electrons and the conduction band is completely void of electrons.

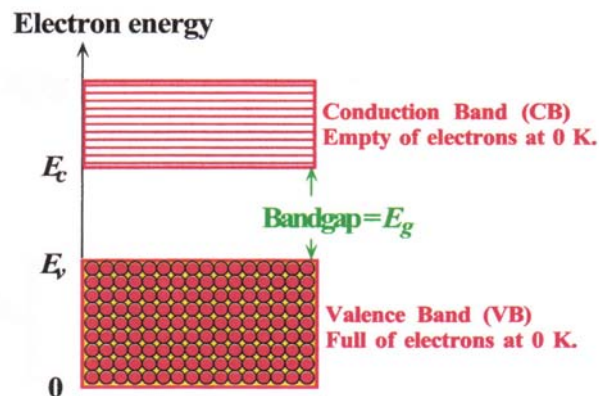


Figure 2. A basic Energy Band diagram at 0 K [After Ref. 3.].

Electrons in the conduction band are called free electrons. These electrons are free to move and allow electricity to conduct through the material. Semiconductors, like silicon, at room temperature have a limited population of free electrons that can be artificially increased or decreased to change the materials ability to conduct electricity. At room temperature the free electrons in the conduction band at equilibrium are caused by thermal generation. Thermal generation is the lattice vibrations that apply enough energy for electrons to jump the bandgap and become free in the conduction band [Ref. 3].

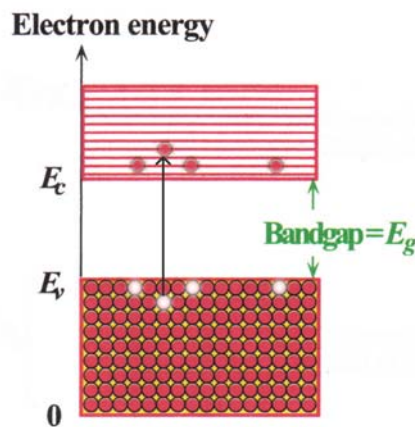


Figure 3. A basic Energy Band diagram at room temperature [After Ref. 3].

### 3. Electrons and Holes

When an electron is excited and moves from the valance band to the conduction band the absences of the electron in the bond is called a hole. These electrons and holes provide a method of current flow through a semiconductor. When a hole is created a free electron will move and fill it. When the electron moves to fill the hole it leaves a hole behind. This gives the appearance of a hole moving in the opposite direction of the electron. This apparent movement is called hole flow. When an electric field is applied to a semiconductor the electrons will move towards the negative side of the field and the holes will move towards the positive side.

### 4. Doping

The electrical properties of pure Si can be greatly changed by introducing small amounts of impurities. Since Si is a Group IV, and has 4 valance electrons, it forms

strong covalent bonds with the other Si atoms in the diamond lattice [Ref. 3]. During a covalent bond two atoms supply electrons to fill each others valance band. This forms a strong bond because both atoms treat the shared electrons as there own [Ref. 3]. If a Group III atom, such as Boron (B), is added as a dopant to a pure Si lattice it will change the electrical properties of the semiconductor. Boron only has three electrons in its valance shell when it bonds with four Si atoms in the lattice one of the covalent bonds will be missing an electron which will be a hole. Nearby electrons can tunnel into this hole and this will make a hole away from the original B impurity. This action is repeated until a free hole is created. Since the B atom creates this hole that will accept an electron therefore it is called an acceptor [Ref. 3]. This doping produces a p-type extrinsic semiconductor.

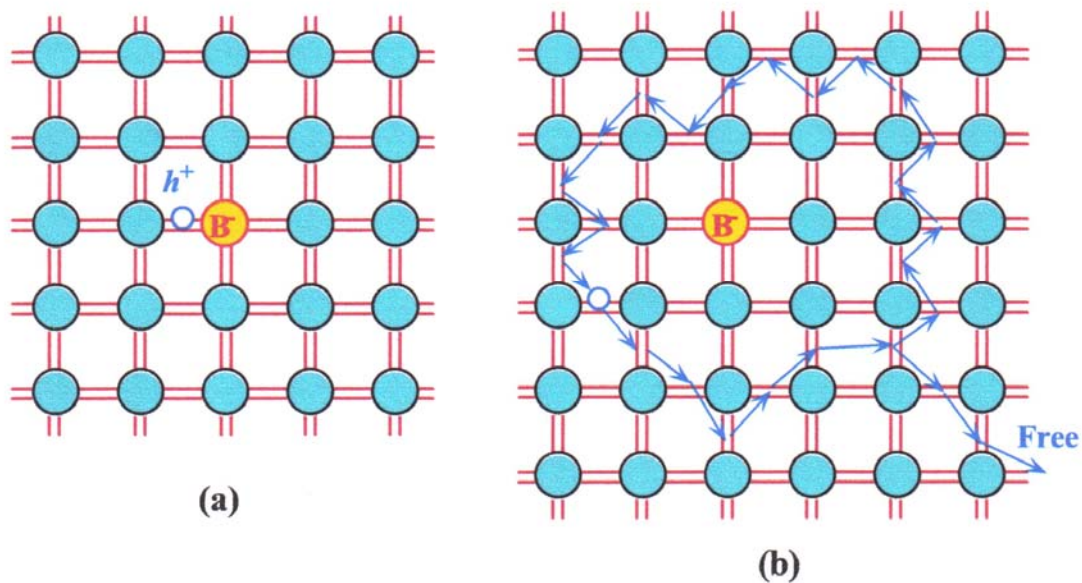


Figure 4. Silicon crystal lattice structure doped with a Boron impurity (a). The hole then can become free when electrons adjacent atoms tunnel to fill the hole next to the Boron impurity [From Ref. 3].

Intrinsic Silicon can also be doped with a Group V element such as Arsenic (As). Since As has five valance band electrons when it bonds with four Si atoms in the lattice structure there is one extra electron which is not used in the covalent bonds. This extra electron continues to orbit the As within the Si lattice structure [Ref. 3]. It takes very little energy to free the extra electron and it is usually freed by the thermal energy of

atomic vibrations at room temperature. Since As donates an electron to the conduction band it is called a donor [Ref. 3]. This type of doping produces an n-type material.

## **B. TUNNEL JUNCTION DIODES**

Majority of the semiconductor devices are produced by combining n-type and p-type materials to produce a pn junction. A Tunnel Junction diode is a special pn junction that produces unique electrical effects. Understanding a basic pn junction is the first step to understanding how a tunnel junction works.

### **1. Unbiased pn Junction**

A pn junction occurs when a sample of pure intrinsic Si is doped n-type on one side and p-type on the other side. There will be a distinct junction between the p-side and the n-side which is labeled M in Figure 5. The p-side of the junction will be doped with acceptor atoms and will have an excess of holes and the n-side will have been doped with donor atoms and will have an excess of free electrons [Ref. 3.]. The holes on the n-side and the free electrons of the p-side are called the majority carriers for the respective sides. The first case examined will be a junction with no applied bias. Due to the high concentration of free electrons on the n-side of the junction, compared to the p-side of the junction, free electrons will diffuse across the junction towards the p-side of the junction. The high concentration of holes on the p-side will cause holes to diffuse to the n-side [Ref. 3]. The holes diffusing into the p-side will recombine with free electrons on the p-side while free electrons from the n-side will recombine with the holes on the p-side. This recombining leaves the regions on both sides of the junction depleted of free carriers when compared to the bulk regions [Ref. 3]. This region around the junction is known as the depletion region.

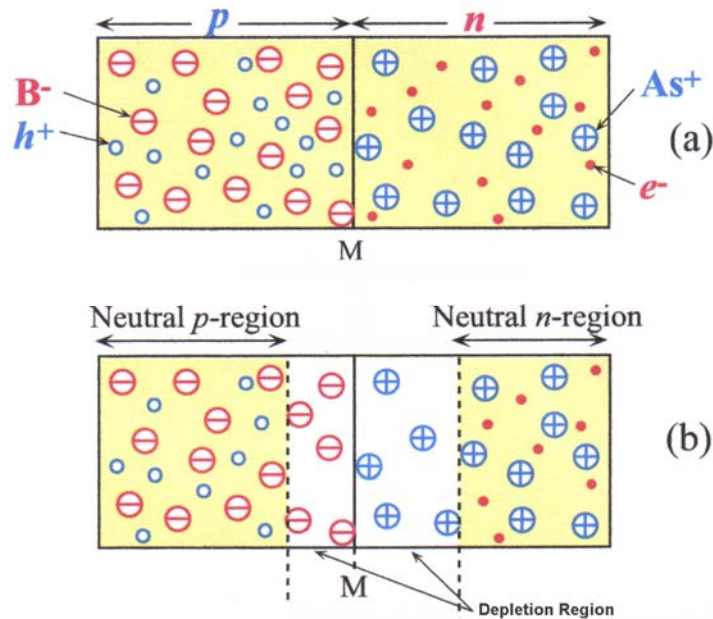


Figure 5. Unbiased Ideal pn Junction [After Ref. 3].

The positive and negative ions in the depletion region form a field. This field is in the opposite direction of diffusion and it attempts to move holes back to the p-region and electrons back to the n-region [Ref. 3]. This force is called drift. As more holes diffuse towards the n-region and more electrons diffuse towards the p-region the field across the depletion region grows stronger. As the field gets stronger it causes move electrons and holes to drift in the opposite direction of diffusion. Eventually an equilibrium is achieved where the carriers diffusing equals the carriers that are drifting. When equilibrium is achieved the depletion region will have a voltage drop across it that is higher voltage on the n-side and lower voltage on the p-side as show in Figure 6 [Ref. 3].



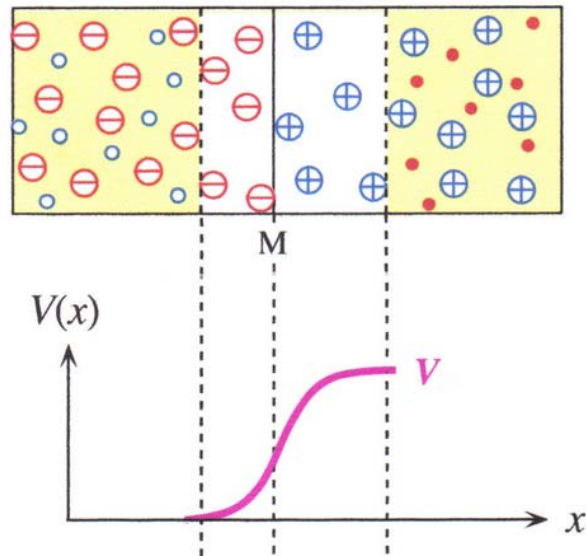


Figure 6. Voltage potential across an un-biased pn junction [After Ref. 3].

## 2. Forward Biased pn Junction

When a battery is connected to a pn junction with the positive side connected to the p-side and the negative side connected to the n-side it will shrink the depletion region size. This happens because the negative side of the battery is connected to the n-side, which has excess majority free electron, this added negative potential will lower the potential drop across the depletion region. This lower potential drop across the depletion region reduces the barrier to diffusion [Ref. 3]. The reduced barrier causes more holes to diffuse across the depletion region towards the n side. The positive side of the battery connected to the p side of the junction causes the electrons to diffuse more rapidly towards the p side. The extra diffusion causes the junction to have excess minority current carriers on both sides.

In the n region of the junction some the extra diffusing holes will recombine with electrons in the region. The electrons lost by this recombination are then replenished by the negative terminal of the battery [Ref. 3]. The diffusion rate can be maintained because the positive side of the battery will replenish the holes that are diffusing. The electrons diffusing from the n side will recombine with holes in the p side. The holes and electrons will both be replenished by the positive and negative terminals of the battery respectfully.

The diffusion and replenishment of holes and electrons through a pn junction provide current flow through the forward biased junction. This current flow is primarily dependent on the minority carriers. Some of the current flow through the junction will come from the drift of majority carriers [Ref. 3]. As the holes diffuse into the n-region the hole diffusion current density ( $J_{D, \text{hole}}$ ) will decrease exponentially. This is due to the hole diffusion length being less than the length of the bulk n-region. As the holes move into the n-region they recombine therefore decreasing the over all  $J_{D, \text{hole}}$ . The free electrons act the same as they diffuse deeper into the p-region. As both of these diffusion currents decrease the majority current carriers in the region increase due to less recombination. This increase in majority carriers and an increase in majority drift current makes up for the lost current density by the minority carriers. This results in a total current that is constant throughout the device as is show in Figure 7.

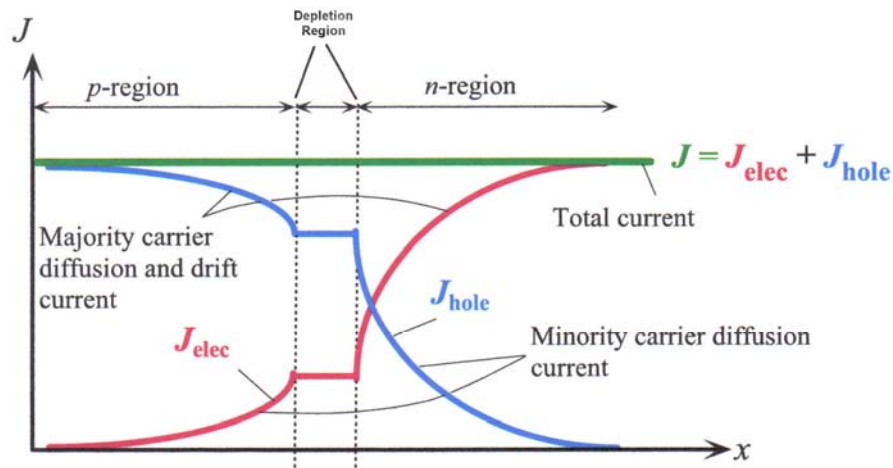


Figure 7. Graph showing the hole and electron current densities that produce a constant total current in the forward biased pn device [After Ref. 3].

When this ideal pn junction is forward-biased the voltage drop across the device remains relatively constant for any current level. For a silicon device the voltage drop across the device is approximately .7 volts when the device is forward biased [Ref. 3]. Figure 8 shows a sketch of a typical Si forward biased I-V curve. The ability of the junction to maintain this relatively constant voltage over a wide range of current is one the most desirable features of the pn Junction diodes.

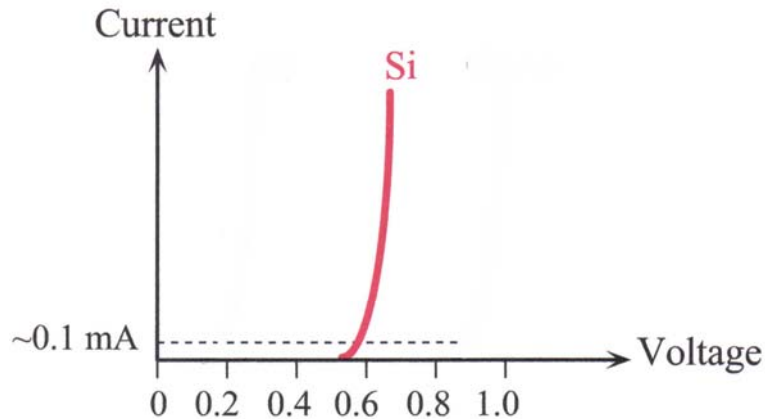


Figure 8. Sketch of a forward biased Si pn Junction [After Ref. 3].

### 3. Reversed Biased pn Junction

If the battery connected to the pn junction is reversed the electrical reaction within the device will change significantly. The battery in a reversed biased diode causes the diode's depletion region to grow. When the positive side of the battery is connected to the n-region it will attract the free electrons in the n-region away from the depletion region. This exposes more of the positively charged donor atoms which will add to the potential drop across the depletion region [Ref. 3]. The negative side of the battery attached to the p-region will attract more holes to the p-side and away from the depletion region leaving a greater population of exposed acceptor atoms. This also results in a growing depletion region. This movement of holes and electrons can not be sustained because they are not being replenished due to the reversal of the battery connections. The applied voltage therefore widens the potential energy barrier and almost no current flows through the device as shown in Figure 9.

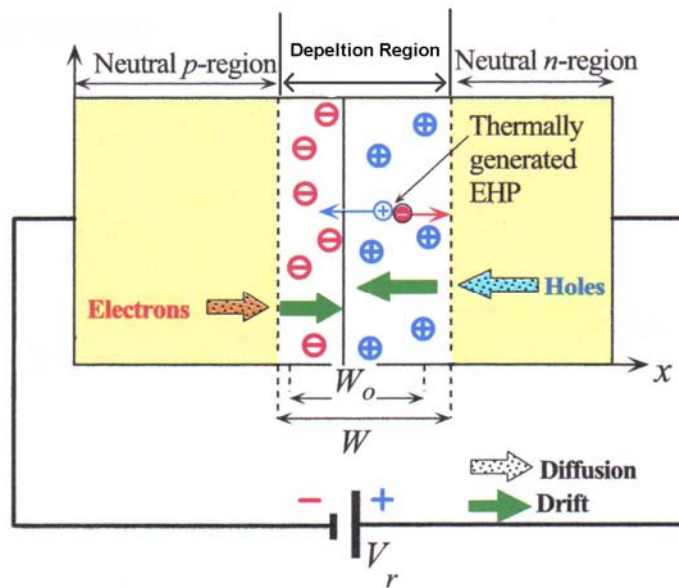


Figure 9. A reverse-bias pn junction showing the enlarged depletion region and the contributing elements of reverse bias current [After Ref. 3].

The current that is able to flow through the device in the reverse biased direction is a small current caused by two sources [Ref. 3]. The first source of this small reverse current is caused by the electric field at the depletion region being larger than the internal field in the device. This larger field can attract some of the small number of holes that are close to the depletion region in the p-region and sweep them across the junction. This small number of holes can be replenished from the diffusion of holes from within the bulk region [Ref. 3]. The same type of current will occur from electrons close to the depletion region in the n-region. The other cause of the small reverse bias current is thermal generation of electron-hole pairs in the depletion region [Ref. 3]. The internal field in the depletion region is strong enough to separate the electrons and the holes. Then the holes and electrons will drift towards their respective neutral region. This drift will add to the external reverse bias current caused by diffusion that was discussed earlier. The overall reverse bias current is still very small, on the order of nano-amps, and makes the pn junction electrically act similar to an open circuit when it is reversed biased. If a large enough voltage is placed across the junction the device will eventually breakdown. A typical forward and reversed biased I-V curve is shown in Figure 10.

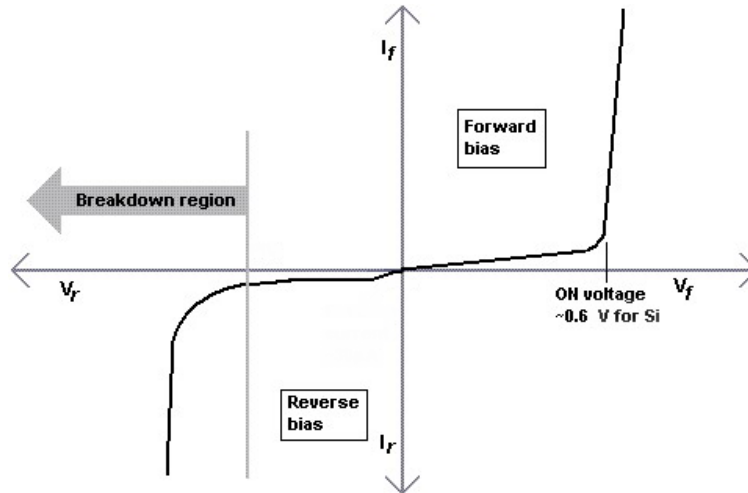


Figure 10. Sketch of a pn junction I-V curve [After Ref. 5]

#### 4. Band Diagrams of pn Junction

One of the most descriptive ways to demonstrate what is occurring in a pn-junction when it is forward and reverse biased is by using energy band diagrams. When intrinsic silicon is doped with acceptor atoms the Fermi energy level ( $E_{Fp}$ ) will be closer to the valance band energy level. If intrinsic silicon is doped with donor atoms then  $E_{Fn}$  will be closer to the conduction band [Ref. 3]. When a system is in equilibrium one of the properties of the Fermi energy level is that it must be continuous. When a junction is formed between a p and n-type material, in an open circuit condition, the Fermi level is uniform throughout the materials and the junction. In the bulk region of the p-material  $E_{Fp} - E_V$  is the same value as if the material was independent of the pn junction and in the n-material bulk region  $E_C - E_{Fn}$  is the same values as if the material was independent. Since the bandgap energy value,  $E_C - E_V$ , is constant in silicon both the conduction and the valance bands must bend to maintain the uniform  $E_F$  as shown in Figure 11.

The bending of the energy bands at the junction is cause by the movement of free carriers at the junction when the two types of materials are connected. When the junction is formed holes will diffuse from the p-side towards the n-side as discussed earlier [Ref. 3]. This hole diffusion will deplete the hole concentration in that region which will cause  $E_V$  near the junction to move away from  $E_{Fp}$  as shown in Figure 11. Free electron near the junction on the n-side will diffuse towards the p-side again depleting this region of its majority current carriers causing  $E_C$  to move away from  $E_{Fn}$ .

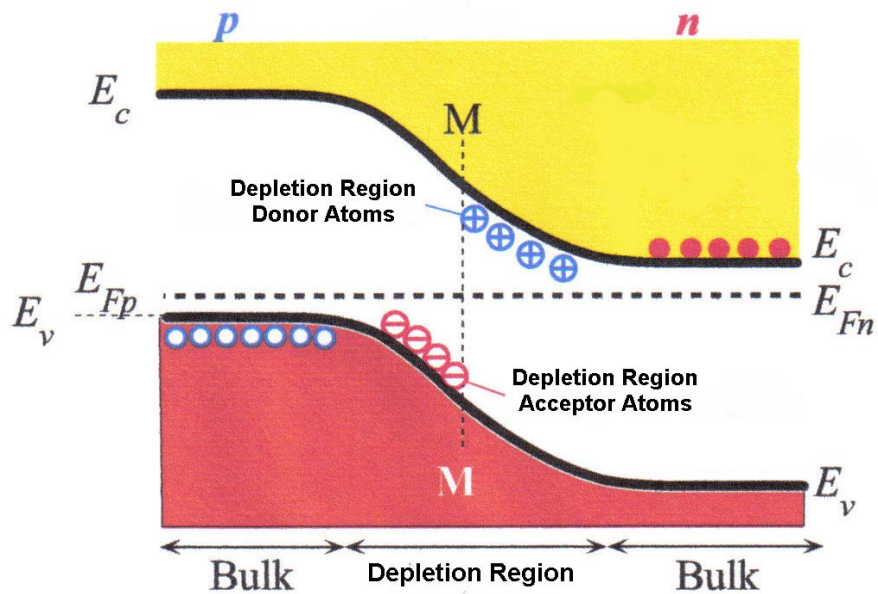


Figure 11. Unbiased band diagram of a pn junction [After Ref. 3]

The band bending is also a result of the built in potential of the junction between the two materials. When the holes and electrons diffuse and recombine around the junction, the depletion region they form has an electrostatic potential [Ref. 3]. The band bending that occurs due to the loss of holes and electrons also is caused by this electrostatic field.

The band diagram will change when the pn junction is forward-biased to reflect the electrical changes that occur within the device. When the junction is forward-biased the depletion region shrinks, as discussed before, and the electrical potential barrier shrinks. This shrinking in the electrical barrier makes it easier for electrons and holes to diffuse across the junction [Ref. 3]. Figure 12 shows a band diagram representation of a forward-biased junction.

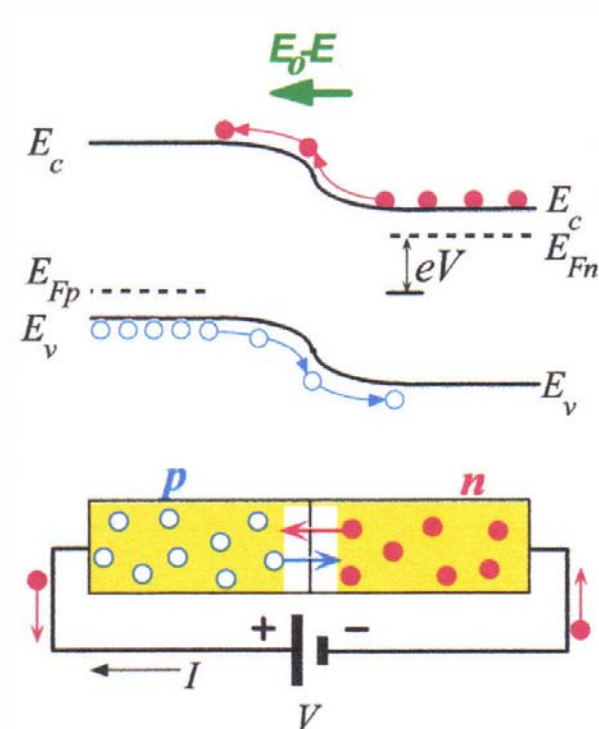


Figure 12. Forward biased pn junction band diagram [After Ref. 3].

When the pn junction is reversed biased the band diagram changes again to represent the new electrical properties of the substance. Since the reverse bias voltage applied to the pn junction adds to the built in voltage barrier the bending to the bands becomes more pronounced. This large potential reduces the diffusion current down to a very small amount as discussed earlier. A demonstration of the reverse bias band diagram is shown in Figure 13.

The small reverse bias current is still generated in the reversed biased junction. When electron-hole pairs are formed in the depletion region, as discussed earlier, the field separates the pairs [Ref. 3]. When looking at the band diagram it shows how the electrons will follow the curving conduction energy band to the n-side and the holes will naturally follow the curving valance band to p-side.

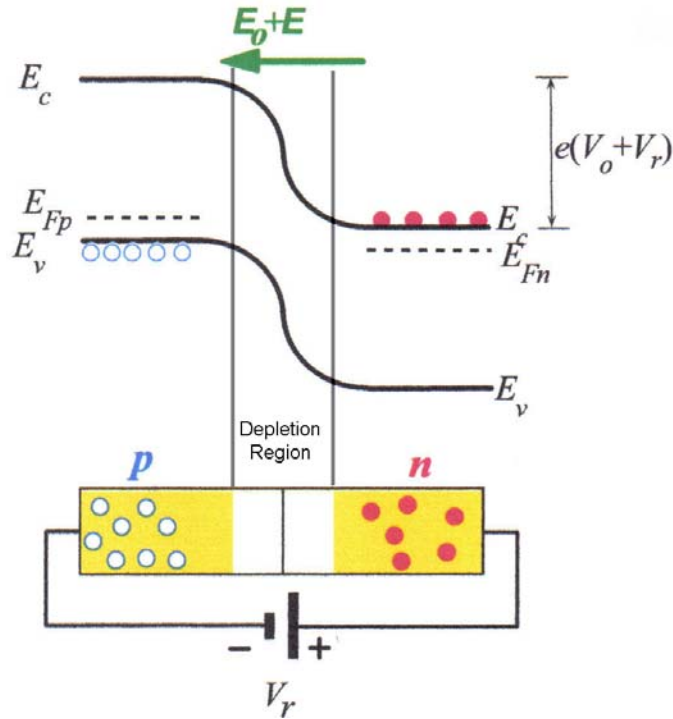


Figure 13. Band diagram showing a pn junction that is reversed biased [After Ref. 3].

Band diagrams provide an easily understandable way to show the electrical properties of a pn junction. This method for explaining the properties of semiconductor devices will be used later to explain more complex concepts.

## 5. Tunnel Junction

When the doping level of p and n-type materials, of a pn junction, are increased to an extremely high level the electrical properties of the junction will change. Highly doped pn junctions are more likely to have a tunneling phenomenon occur and these diodes are sometimes called Esaki tunnel diodes [Ref. 8]. When using classical examples, free carriers that cross the junction have traditionally had an energy level at least equal to the potential barrier level at the junction but when tunneling phenomenon occurs these carriers do not need to meet these energy requirements. During tunneling phenomenon an electron can penetrate through a thin depletion region. Until this point semiconductor junctions that were discussed were made up of non degenerate doped semiconductors. Non degenerate doped semiconductors are semiconductors that are doped so that the Fermi energy level is at least  $3kT$  from the valance or conduction band. Where  $k$  is equal to Boltzmann's constant and  $T$  is temperature in Kelvin [Ref. 6]. At



room temperature  $kT = 0.0259$  eV [Ref. 6]. To produce a pn junction that would be capable of operating as an Esaki diode the p-type material must be doped with an acceptor concentration ( $N_A$ ) typically greater than  $10^{20}$   $\text{cm}^{-3}$  [Ref. 9]. Also the n-type material would have to have a donor concentration ( $N_D$ ) greater than  $10^{20}$   $\text{cm}^{-3}$ . Having a very high impurity concentration will cause the depletion layer shrink and become very narrow.

The narrow depletion region is a requirement for tunneling to occur but it is not the only condition to be met. For tunneling to occur there must also exist occupied energy states on the side that the electron moves from on the same energy level as empty states on the side that the electron is moving too. An example of this is shown in Figure 14.

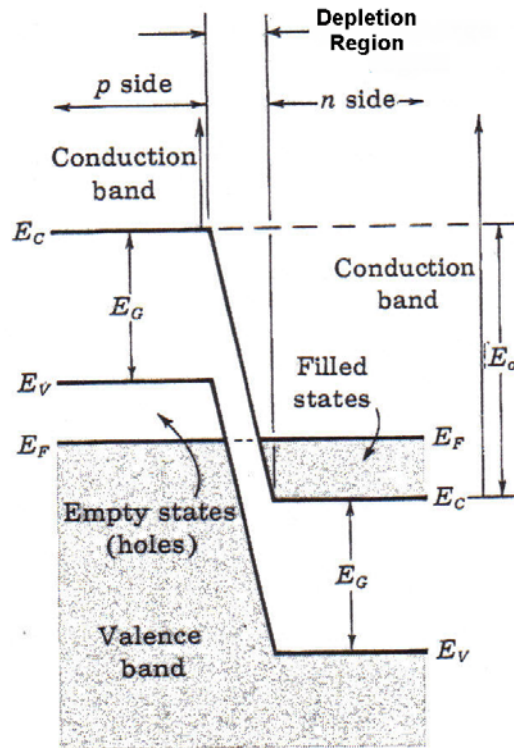


Figure 14. Energy band diagram of a heavily doped pn junction in an open circuit condition. [After Ref 9].

To place the free electrons and the empty states on the same level the junction will have to be doped to a concentration which will place the Fermi energy level out of the bandgap

region. In past example the  $E_F$  has always been in the forbidden band but by using the basic equation for  $E_F$  it can be shown that in highly doped material that  $E_{Fp}$  and  $E_{Fn}$  can be placed below and above the valence and conduction bands respectively [Ref. 9].

$$E_{Fn} = E_C - kT \ln \frac{N_C}{N_D} \quad \text{Where } N_C \approx 10^{19} \text{ cm}^{-3}$$

Since for a heavily doped junction  $N_D > N_C$  the natural log in the above equation will produce a negative value. Therefore  $E_{Fn}$  will be greater than  $E_C$  since  $kT$  does not change with a change in dopant concentration. Similarly using the basic equation to find  $E_{Fp}$  it is demonstrated that  $E_{Fp}$  for a heavily doped p-type material will be below  $E_V$  [Ref. 9].

$$E_{Fp} = E_V + kT \ln \frac{N_V}{N_A} \quad \text{Where } N_V \approx 10^{19} \text{ cm}^{-3}$$

Both of these conditions are demonstrated in an open circuit condition in Figure 14. Figure 14 also shows that there are no filled charge states at the same level as free charge states and therefore no tunneling can occur in this open circuit condition.

Tunneling phenomenon in a highly doped pn junction produces very different current and voltage characteristics than in a normal pn junction diode. Figure 15 shows a basic I-V curve of an Esaki diode.

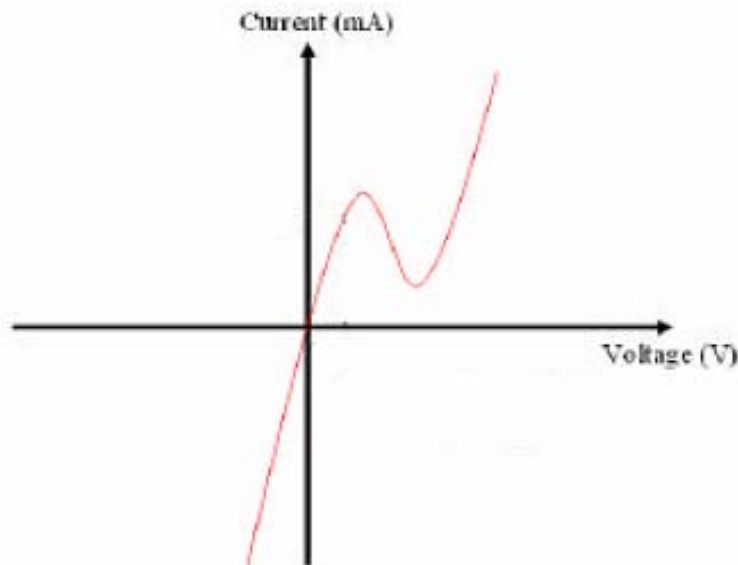


Figure 15. Sketch of a basic I-V curve of a tunneling diode [After Ref. 14].

Using band diagrams, of the tunnel diode, in different states of bias the I-V curve can be easily explained. For all the band diagram explanations of the tunneling diode the p side of the junction is going to be maintained at 0 V while the voltage level on the n-side of the material is adjusted.

The first condition that will be examined is the reverse-biased condition. When a reverse bias is applied to the junction the valance and conduction bands will bend more sharply then during the open biased condition increasing the barrier height. This increase in barrier height, due to the shifting down ward of the n-side bands, will cause some of the filled states in the p-side to line up directly across from empty states in the n-side. This allows electrons to tunnel through the barrier allowing the reverse bias current to increase as the reverse bias voltage increases [Ref. 9]. This is shown in the band diagram in Figure 16 and the effect can be seen in the reverse voltage area of the I-V curve.

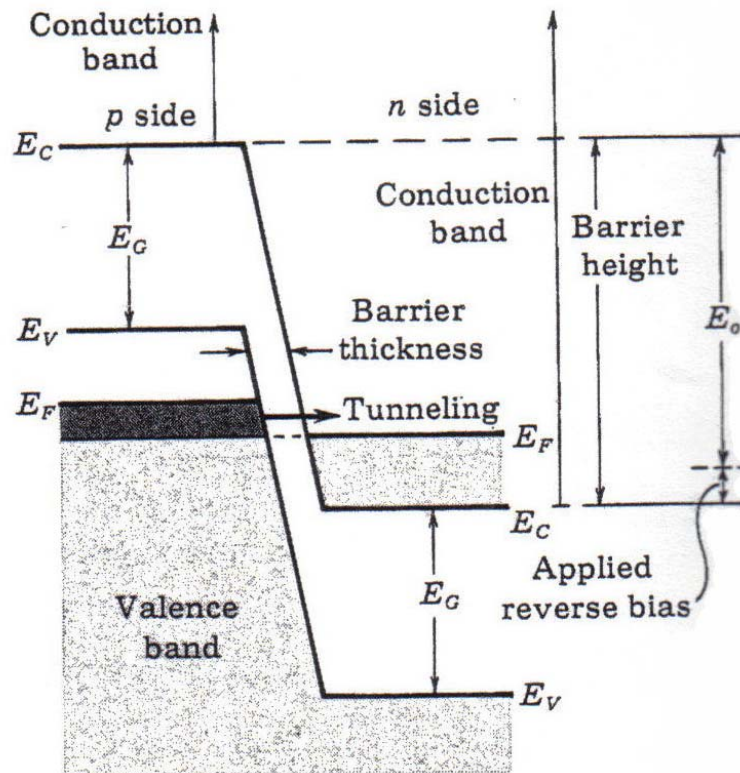


Figure 16. Energy band diagram on a heavily doped p-n diode in a reverse bias condition [From Ref. 9].

The next condition examined will be with a small forward bias applied to the junction. Again the p-side of the material will be maintained at 0 V and the voltage will be applied to the n-side of the material and when the energy bands shift it will be referred to as the n-side moving in reference to the p-side. When as small forward bias is applied to the junction the potential barrier will be reduced this will cause the n-side energy bands to move upward. When this occurs there are now filled states on the n-side of the material and empty states at the same level on the p-side of the material. This allows electrons to tunnel from the n-side to the p-side allowing the initial forward bias that is seen in the I-V curve [Ref. 9]. Figure 17a shows the energy band diagram with a small forward bias applied to the n-side of the material.

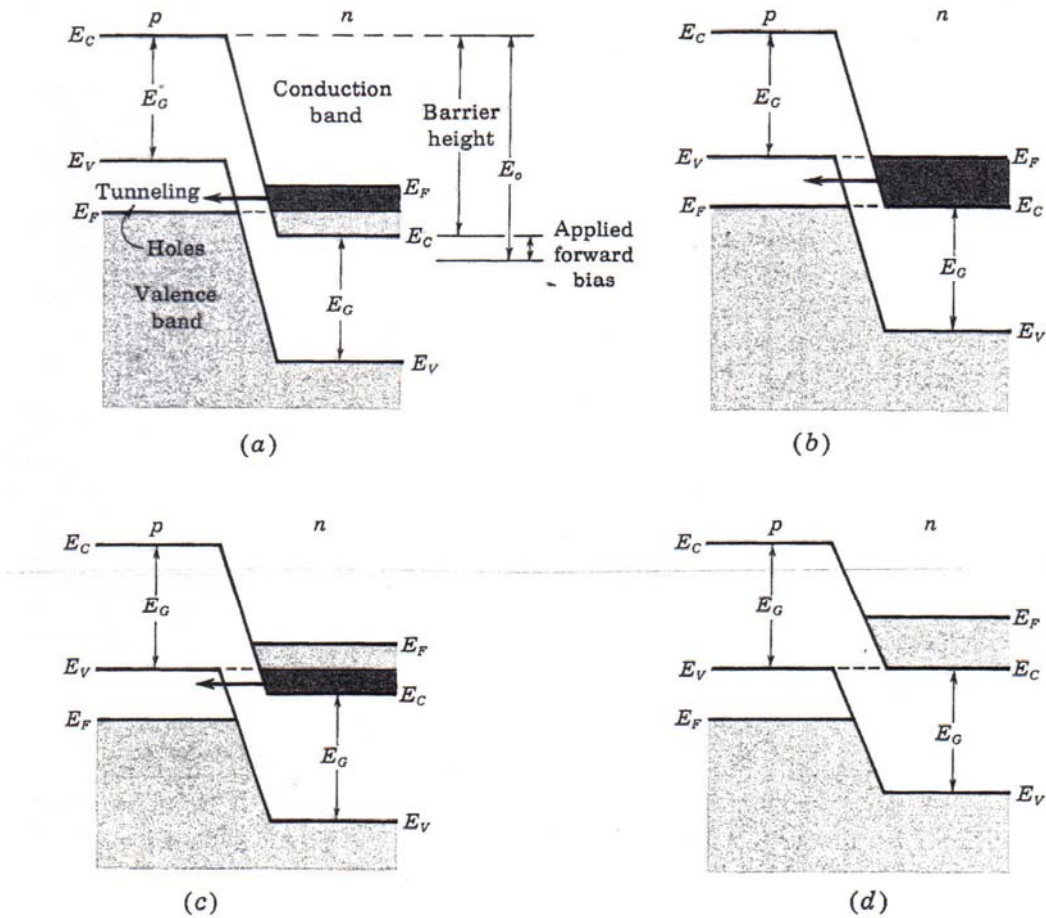


Figure 17. Energy band diagrams of a tunnel diode that is forward biased. The bias voltage is being increased from figure (a) to figure (d) [From Ref. 9]

When the forward bias on the junction is increased more of the electrons in filled states on the n-side of the junction will be at the same energy level as empty states on the p-side of the junction. This will cause the maximum tunneling effect of electrons moving from the n-side to the p-side. This is when the current peak will occur on the I-V curve. This stage is shown in Figure 17b. As the forward bias is increased more the junction acts more like Figure 17c. Some of the occupied states on the n-side no longer line up with vacant states on the p-side. Hence the forward bias current will start to decrease as fewer electrons are tunneling through the barrier. This voltage level is represented on the I-V curve by the decrease in forward bias current. As the bias voltage is continued to increase the junction moves to a point where no tunneling is occurring. This is represented in Figure 17d. At this bias point the occupied states on the n-side have moved so far that they are no longer on the same energy level as any of the empty states. This area is shown in the low current area of the I-V curve. If the forward bias is further increase the diode will respond with normal forward bias current of the pn junction described in earlier sections [Ref. 9]. The negative resistance portion of the tunnel diode makes it useful in many application including oscillators, amplifiers, switches, and for connecting the layers of a multi-junction solar cell. Solar applications are the driving motivation behind this thesis and next section will cover solar cells and why the tunnel junction is important.

## **C. SOLAR CELLS**

A solar cell in its most basic form is a simple pn junction. This pn junction will have the ability absorb solar energy and convert it to electrical energy. The electrical energy produce per individual cell is typically small but when any cells are placed together the overall energy can be significant. To build the most efficient modern solar cells designers must build multijunction solar cells. These multijunction cells have two, three or four pn junction cells that are attached using tunnel diodes between the cells. These cells are the primary type used in current space applications. To understand the importance of the tunnel junction to these cells first solar cells basics must be explained.

### **1. Basic Single Layer Cell**

The most basic type of simple solar cell that will be discussed is an n-on-p solar cell. This type of cell has an n-type material that is layered on top of a p-type material

base. The n-type material is referred to as the emitter and the p-type as the base [Ref. 11]. When energetic photons from a light source enter into the pn junction produced by the emitter and the base they can transfer enough energy to valance electrons to move them across the band gap and into the conduction band [Ref. 11]. This is accomplished by the generation of electron-hole pairs (EHP) in the depletion region. Once these pairs are created the electron and hole will be pulled to opposite sides of the region due to the potential field across the junction. This will cause a current flow that is proportional to the intensity of the incident light. Figure 18 shows a simple n-on-p solar cell that will be used to further explain the characteristics of a simple solar cell.

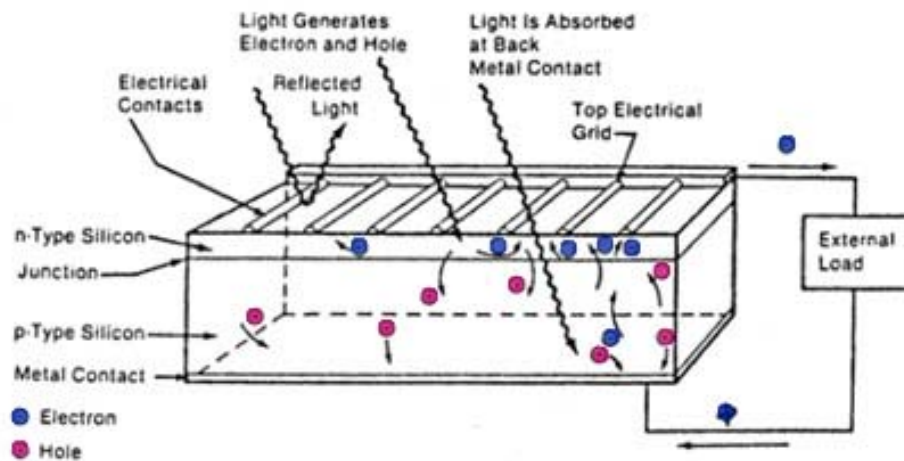


Figure 18. Simple n-on-p solar cell with an external load [After Ref. 11].

There are several challenges when designing a solar cell that can be seen in the simple cell show in Figure 18. One of the challenges is connecting contacts to the pn junction that will not block the light from entering the solar cell. This is accomplished by using a grid of very thin metal contacts [Ref. 11]. This grid will still block some photons from entering but majority of the incident light will reach the junction. Another challenge that is involved in producing a solar cell is ensuring the light is not reflected from the surface instead of penetrating. One method to prevent the reflection is use an anti-reflective coating of  $MgF_2$  or  $ZnS$  [Ref. 12]. Another more sophisticated method of preventing reflection is to use microgrooves. Microgrooves are texturing the surface of

the solar with very small features that reduce the amount of incident light that does not penetrate the surface. An example of this texturing is shown in Figure 19. When the incident light strikes one of the microgrooves a portion of the light will enter the cell and any light reflected will be directed towards another groove. The last method that can be used to improve light absorption in a single layer solar cell is to have a very reflective metal surface connected on the base of the cell. This surface would reflect any light that was not absorbed in the first pass back into the cell so that there is the possibility it being absorbed [Ref. 11].

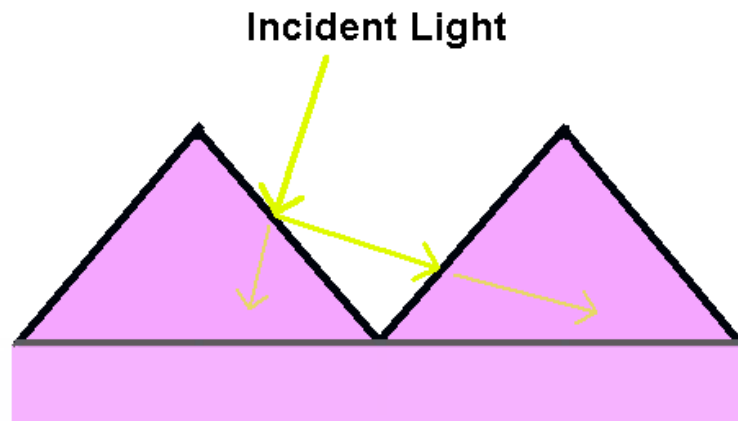


Figure 19. Incident light striking and reflecting off the surface microgrooves.

Solar cell performance is measured by evaluating several key characteristics. The key measurements are short-circuit current, open-circuit voltage, fill factor, maximum power and efficiency [Ref. 11]. The first examination will be of a single cell in an open circuit condition. As the light strikes the cell electron-hole pairs are formed and the potential field separates the charges to the separate sides of the junction. Since the electrical contacts are in an open circuit condition the potential charge field increase. This phenomenon continues until an equilibrium condition is met where the electric field at the junction is at a point where the electron-hole pairs will recombine vice separate. This voltage is the open-circuit voltage and it is the highest voltage that can be generated by the solar cell [Ref. 11].

The second condition that will be examined is the circuit under a short circuit condition. When the junction is short circuited the generated electron-hole pair are quickly draw to the opposite sides of the cell and out of the cell through the metal contact. It is the condition in which the maximum current of the cell is measured. This current will be dependent on the light intensity and the ability of the cell to absorb this light [Ref. 11]. This condition will be used along with the open circuit condition to determine some of the cells other key characteristics.

Solar cells I-V curve is made using the values determined from the open and short circuit cases. The short-circuit current will be the y-axis intercept of the I-V curve while the open-circuit voltage will form the x-axis intercept. When a very small load is connected to the solar cell the current through the load will be approximately the same as the short-circuit current and the voltage will be very small. As the resistance of the load is increased the voltage drop across the load will increase and the current delivered by the cell will decrease. When the voltage gets close to the open-circuit voltage the electron-hole recombination will reduce the available current. The closer to the open-circuit voltage the faster the current delivered decreases. A typical I-V curve can be seen in Figure 20.



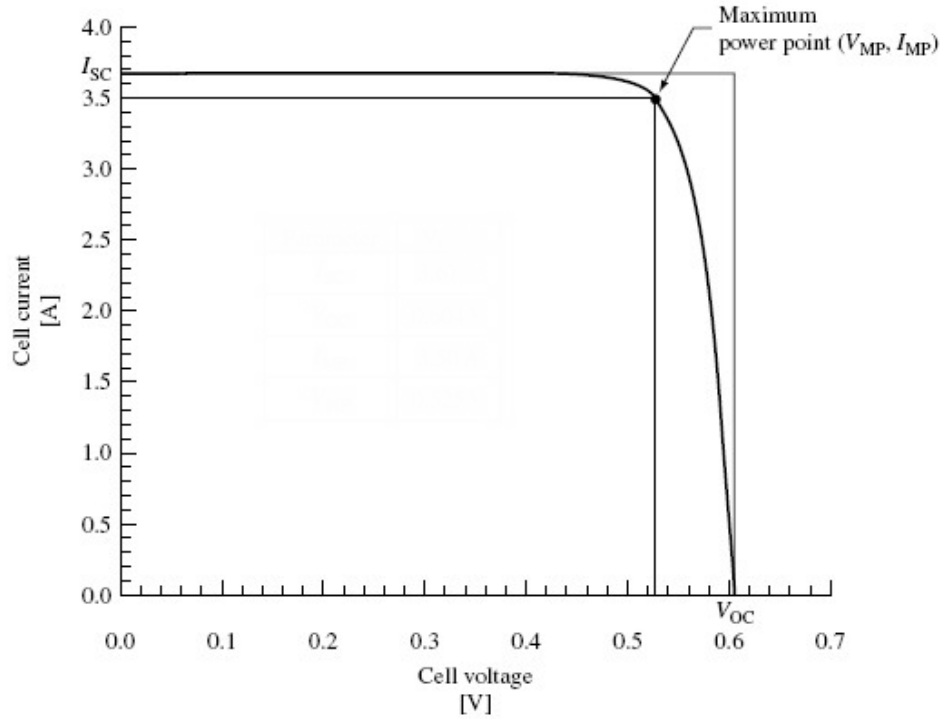


Figure 20. A basic current-voltage curve of a silicon solar cell [After Ref. 10].

When the I-V curve is examined it can be seen that a compromise of current and voltage values can be met that will deliver the maximum power for a given light intensity. This power can be used to determine the fill factor (FF) using the following equation.

$$FF = \frac{P_{\max}}{V_{oc} I_{sc}}$$

The fill factor is a figure of merit for solar cell design [Ref. 6]. The last property to be discussed is a solar cell's efficiency. Solar cell efficiency ( $\eta$ ) is calculated using  $P_{\max}$  and  $P_{\text{avail}}$ .  $P_{\text{avail}}$  is the amount of radiated power striking the solar cell area from the light source [Ref. 11]. The sun is the light source used in this thesis and it delivers  $136.67 \text{ mW/cm}^2$  at Air Mass Zero (AM0), which is the light intensity delivered to satellites in Earth's orbit [Ref. 11]. The solar cell efficiency is calculated using the following equation.

$$\eta = \frac{P_{\max}}{P_{\text{avail}}}$$

The last concept about the basic solar cell that must be discussed is the factors that affect a cell's performance. The first factor affecting the cell's performance is the bandgap of the material being used and the spectral intensity of the light source. Since the bandgap energy determines the amount of energy that a photon must have to create an electron-hole pair it is the most important factor. The energy of a photon is determined using the wave length ( $\lambda$ ) of the incident photon, Planck's constant ( $h$ ) and the speed of light ( $c$ ) [Ref. 11].

$$E = \frac{hc}{\lambda}$$

If  $h = 4.14 \times 10^{-15}$  eV-sec and  $c = 2.998 \times 10^{10}$  cm/s the above equation can be simplified to the below expression [Ref. 6].

$$E[\text{eV}] \approx \frac{1.24}{\lambda[\mu\text{m}]}$$

Therefore, a cell of a given semiconductor will only produce power when it is struck by light of a certain wavelength. This performance issue can be improved when using multijunction solar cells.

## 2. Multijunction Solar Cells

Multijunction solar cells provide the ability to use more of the light spectrum that would not be fully capitalized when using a single layer cell. When designing a multilayer cell the designer will use different semiconductor materials for each layer. Each of layers will have different bandgaps that will take advantage of different energy photons. The cells will be stacked in series so that there voltages will add together giving the multi-junction cell a larger open-circuit voltage and result in larger power for the same given area [Ref. 11].

### Typical IV Characteristic

AMO (135.3 mW/cm<sup>2</sup>) 28°C, Bare Cell

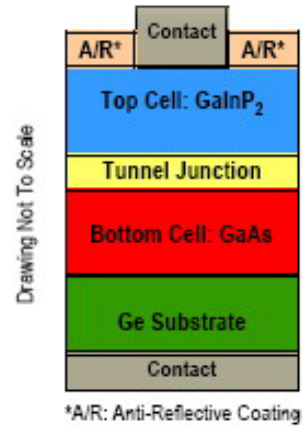
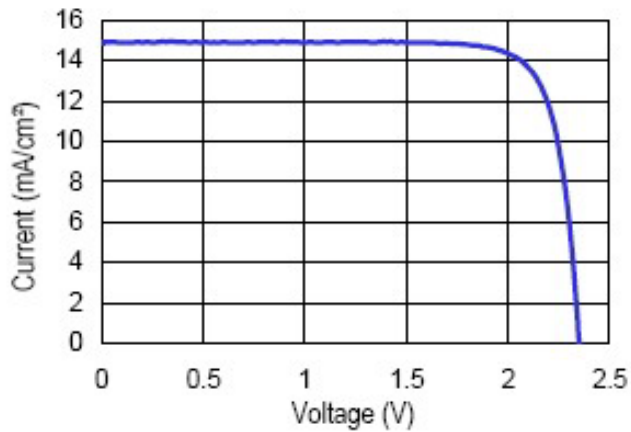


Figure 21. An example of a typical dual junction Solar Cell and its corresponding current-voltage curve. Taken from SpectroLab's GaInP<sub>2</sub>/GaAs/Ge Dual Junction Solar Cells data sheet.

The layer selection of the multijunction solar cell is critical. Since the multijunction solar cell is connected in series the current of the entire structure will be limited by the cell with the lowest current level. The designer would place the cell that generates the lowest current on the top of the structure [Ref. 11]. This would allow that low current cell to receive the most light so that it would generate its maximum current. The other cells in the structure will receive their light after it passes through the top layers. This will reduce the percentage of max current that this layer will produce. The size of the bandgap of a material used in a cell is inversely proportional to the I<sub>SC</sub> of that cell [Ref. 11]. Therefore the larger bandgap are used in the top cells.

### 3. Solar Cell Application of the Tunnel Junction

The tunnel junction is used when connecting the different layers of a multijunction solar cell [Ref. 11]. When developers first started making multijunction cells they did not use a tunnel junction to connect the cell. They would place one n-on-p single layer cell on top of another n-on-p cell. When these two cells are placed on top of one another they formed a structure that is seen in Figure 22.

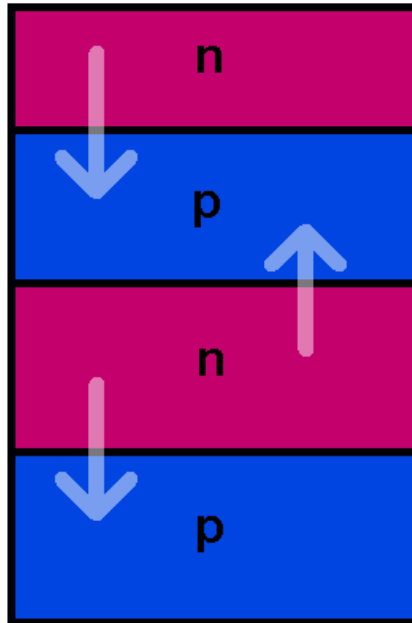
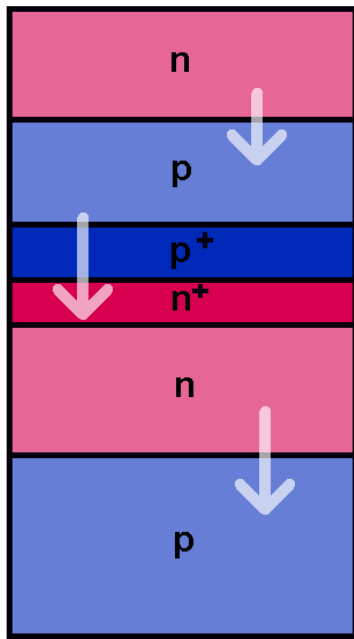


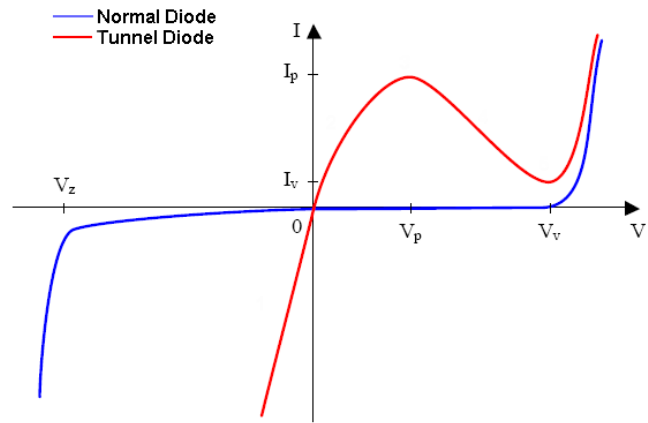
Figure 22. A simple sketch of a dual junction cell with no tunnel diode.

This type of design has a major flaw. The junction between the cells forms a parasitic pn junction. This junction will be a forward bias pn junction. Since the voltage drop across a forward bias pn junction is high relative to the voltage produced by a solar cell, this junction's field would be too large for the top layer of the device to overcome [Ref. 11].

To counter the problem of parasitic junctions, modern solar cells use a highly doped, thin tunnel junction that is placed between the different layers of the cell. This is shown in Figure 23a. The tunnel junction provides a solution because of the tunnel junction's significantly different current-voltage characteristics. Figure 23b shows a typical tunnel junction IV curve and normal pn diode on the same axis. It can be seen that the tunnel junction allows a forward bias current that occurs at a much lower voltage value than the comparable pn diode [Ref. 11]. This allows the current to flow through the junction without the significant voltage drop.



**(a)**



**(b)**

Figure 23. (a) Shows a dual junction solar cell with a highly doped tunnel junction in the middle. (b) Shows a normal and tunnel diode I-V curve [After Ref. 12].

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### III. SILVACO'S ATLAS DEVICE SIMULATOR

ATLAS is Silvaco International's primary TCAD device simulator and has the ability to model devices of many different materials and physical characteristics [Ref. 1]. The primary method of interfacing with the ATLAS simulator is using Silvaco's Deckbuild operating environment. Devices can either be completely constructed in Deckbuild to be run by ATLAS or they can be built using Silvaco's ATHENA device frame work simulator. Figure 24 shows a flow chart that describes how the different programs of Silvaco's TCAD suite interact with the ATLAS device simulator.

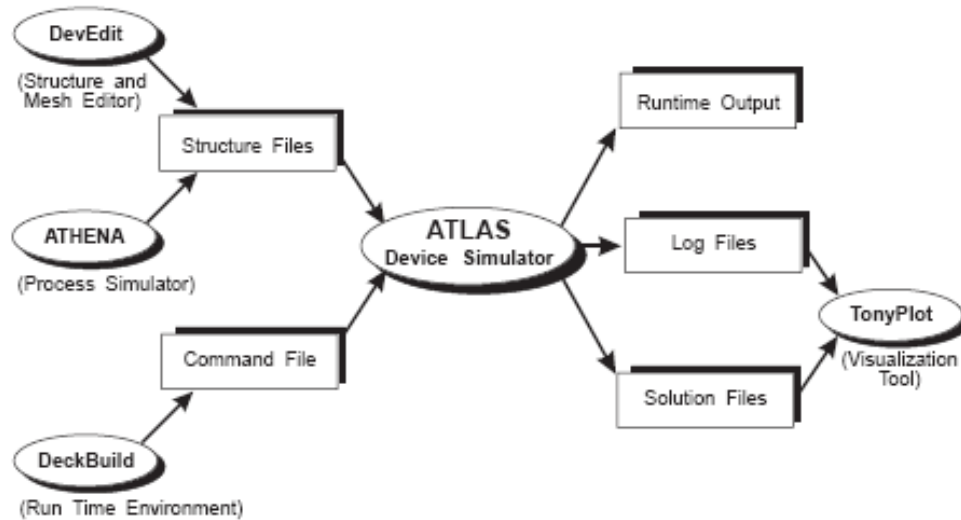


Figure 24. A flow chart showing ATLAS inputs and outputs [From Ref. 1]

Majority of the work in this thesis and past thesis uses Deckbuild to create the device to run in ATLAS so that will be the main focus of explanation. ATLAS will produce log files, solution files and runtime output. Copies of the runtime output files for all the tunnel diode simulations performed in this thesis can be viewed in Appendix B.

#### 1. Modes of Operation

All simulations in this thesis were run using Deckbuild to provide the device structure information to the device simulator ATLAS. ATLAS has the ability to run in several different modes that are with Deckbuild including Interactive Mode, Batch Mode, No Windows Batch Mode and inside Deckbuild [Ref. 1]. Inside Deckbuild is the

recommended method by Silvaco and will be the only way ATLAS is run during this thesis [Ref. 1]. Each time the designer wants to run ATLAS inside Deckbuild the first programming line should be:

*go atlas*

This input will start ATLAS simulator and allow it to input the rest of the conditions stated in the code in Deckbuild [Ref. 1].

## 2. Order of Commands

The order in which commands are entered into Deckbuild are very important to ensure that ATLAS runs the program correctly. ATLAS needs to have the commands in the proper order or it will give an error message [Ref. 1]. Silvaco breaks the commands into five groups and each group will have several statements in that group. The statements in each group in most cases must be run in order. Figure 25 shows the groups and the order in which they should be inputted into Deckbuild.

<i>Group</i>		<i>Statements</i>
1. Structure Specification	————	MESH REGION ELECTRODE DOPING
2. Material Models Specification	————	MATERIAL MODELS CONTACT INTERFACE
3. Numerical Method Selection	————	METHOD
4. Solution Specification	————	LOG SOLVE LOAD SAVE
5. Results Analysis	————	EXTRACT TONYPLOT

Figure 25. ATLAS command groups and the major statements in each group [From Ref. 1].

This thesis will use ATLAS five command groups to describe how to use ATLAS to build and simulate a simple pn junction diode.



### 3. Structure Specification

Structures of devices to be simulated are entered in plain text into the Deckbuild input deck. To properly build a device in Deckbuild a designer must define several key parameters to get an accurate result. The key parameters in the structure command group include the following; a two or three dimensional grid, called the mesh, the mesh must be divided into regions, electrode locations and materials must be defined, doping levels and dopants must be defined [Ref. 1]. When programming in Deckbuild the # is used to indicate that the line is only a programmers note and not part of the program. The code for the example diode can be found in Appendix A.

The mesh is the two or three dimensional grid used as the frame work to build your device. In this thesis all the device designs will be using a two dimensional grid. The mesh statement will define the boundaries of the device you are building and the resolution of detail. The first mesh command must be the mesh space multiplier command [Ref. 1]:

*mesh space.mult=<value>*

This command will tell ATLAS the scaling factor of the mesh. The mesh will be less dense for a large number and denser for a smaller number. The value for this is normally set to equal 1. Figure 26 shows an example of a mesh with a *space.mult* value of 5 compared to a mesh with a value of 1.

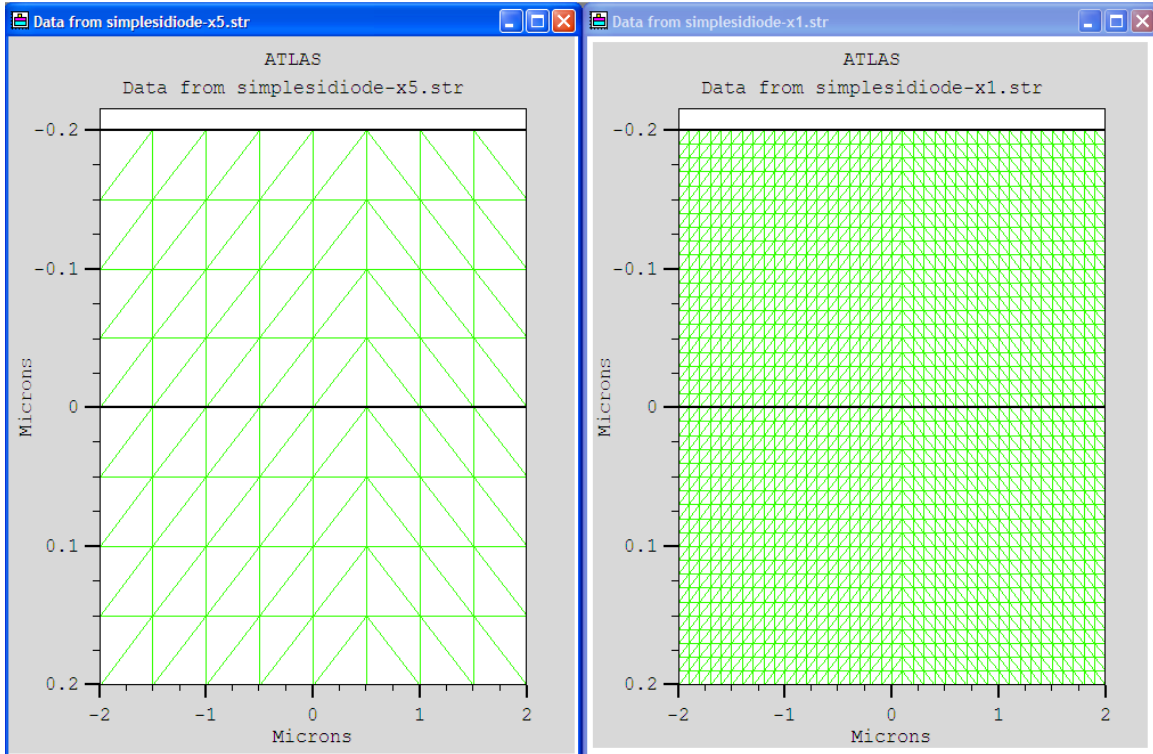


Figure 26. Comparison of mesh grids when using a multiplier of 5 and 1.

The next step to defining the mesh is to specify the actual grid make up. Mesh statements are entered in as vertical and horizontal lines in microns and as distance from the center line. ATLAS will automatically adjust the grids to represent the desired resolution the user has entered [Ref. 1]. ATLAS divides the grid using a triangle format. The user can use a higher resolution over areas of the device that the user wants more detail. Typically a high grid resolution is used at junctions and material boundaries. This can be seen in Figure 27 which shows the ATLAS mesh and the mesh statements of a simple pn diode. Notice the tighter grid along the junction in the middle of the device.

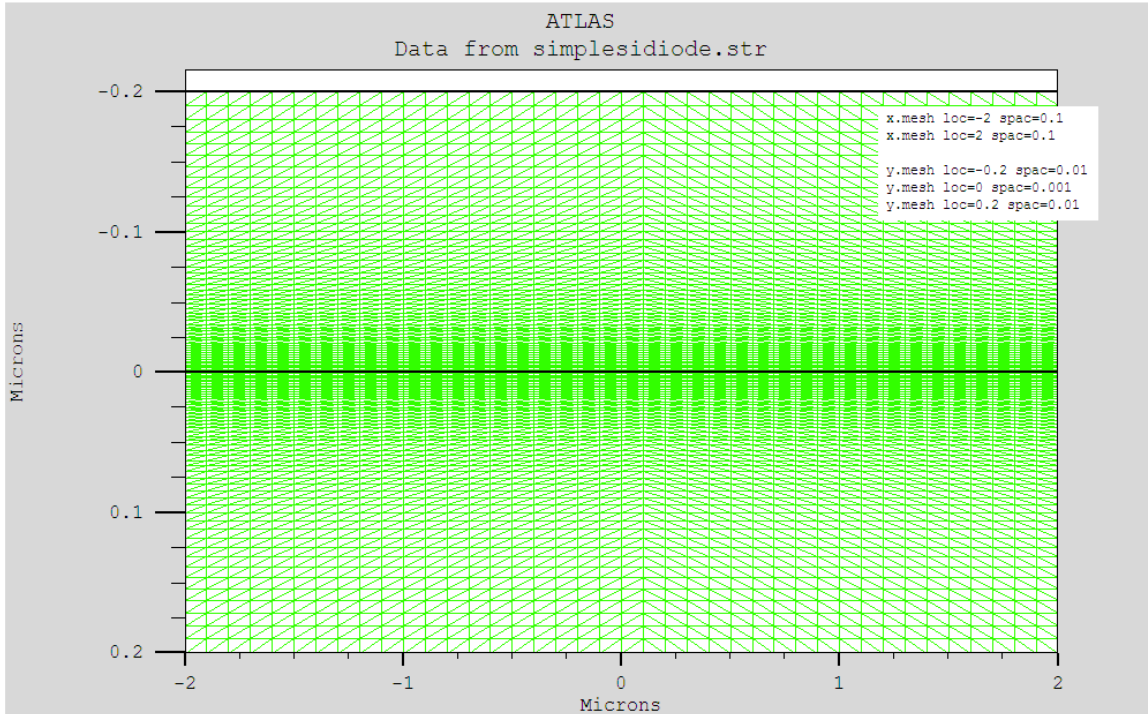


Figure 27. Mesh statements and the resulting mesh for a simple Si pn diode.

After the designer has defined the device mesh, they will next have to define the regions of the device. The regions will be used to assign materials and properties to the device. The regions must be defined along the mesh lines and the statements will be similar to those used for the mesh states. ATLAS allows the user to define up to 200 different regions for one device. If the designer overlaps any of the two regions ATLAS will assign the material type to the last region that was defined. The entire two dimensional mesh area must be defined into regions or ATLAS will not run successfully [Ref. 1]. The designer will list the material type when defining a region but to define the material properties of the material type the design must wait until second command group [Ref. 1]. Regions can be defined using cylindrical coordinates but this type of region definition is not used in this research so it will not be addressed. Figure 28 shows the region statements and ATLAS regions for a simple pn junction diode.

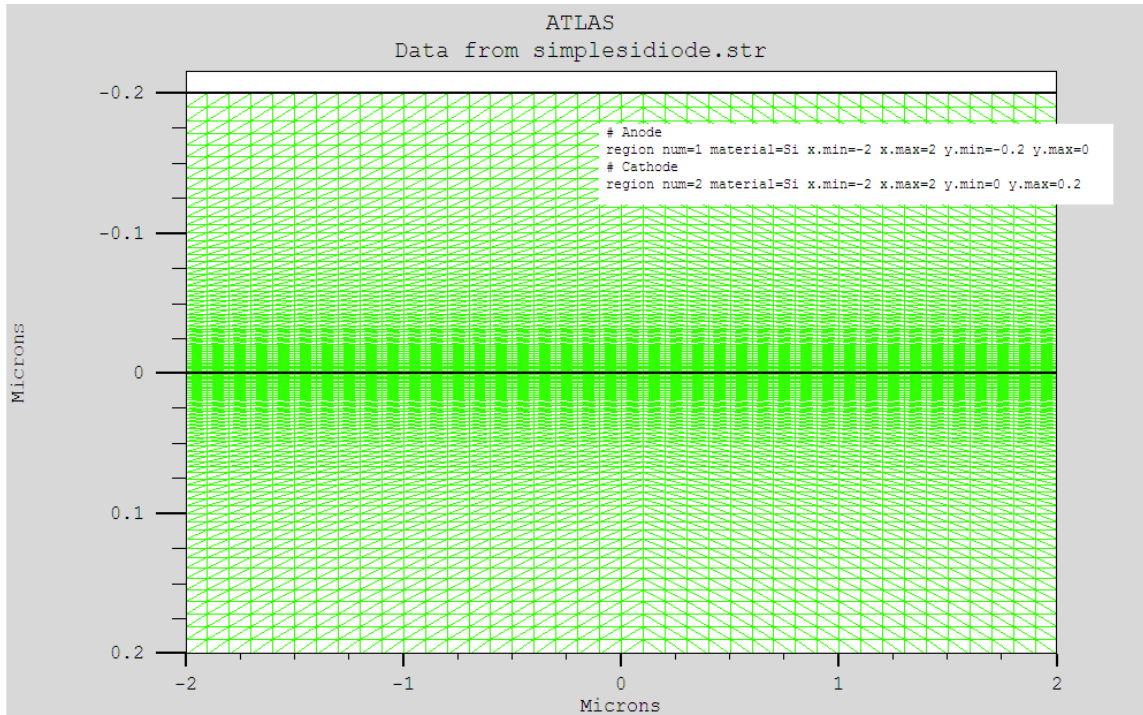


Figure 28. ATLAS region boundaries and region statements for a simple Si pn diode.

For ATLAS to find the electrical properties of the structure the designer must define the location of the electrodes. The designer must specify the electrode name and where it is located. ATLAS requires a minimum of one electrode and has a maximum limit of 50 electrodes for one device [Ref. 1]. The electrodes can be specified as a certain material or you can leave them undefined and ATLAS will use an ideal conductor [Ref. 1]. In the example the electrode were left undefined to get a perfect contact.

The next action, doping, is one of the most important actions a designer does to affect the electrical properties of the structure they are designing. Silvaco allow the designer to specify the type of dopant and the concentration. It also allows the designer to specify the distribution of the doping material. ATLAS has the ability to distribute the dopants in a uniform or Gaussian profile [Ref. 1]. The uniform doping profile has an easy set of commands to dope the material exactly how the design wishes it. Figure 29 shows the doping concentration of a pn diode; notice how the impurity concentrations change in the junction region. Figure 29 also give the commands to produce this doping in the upper right hand corner of the Tonyplot.

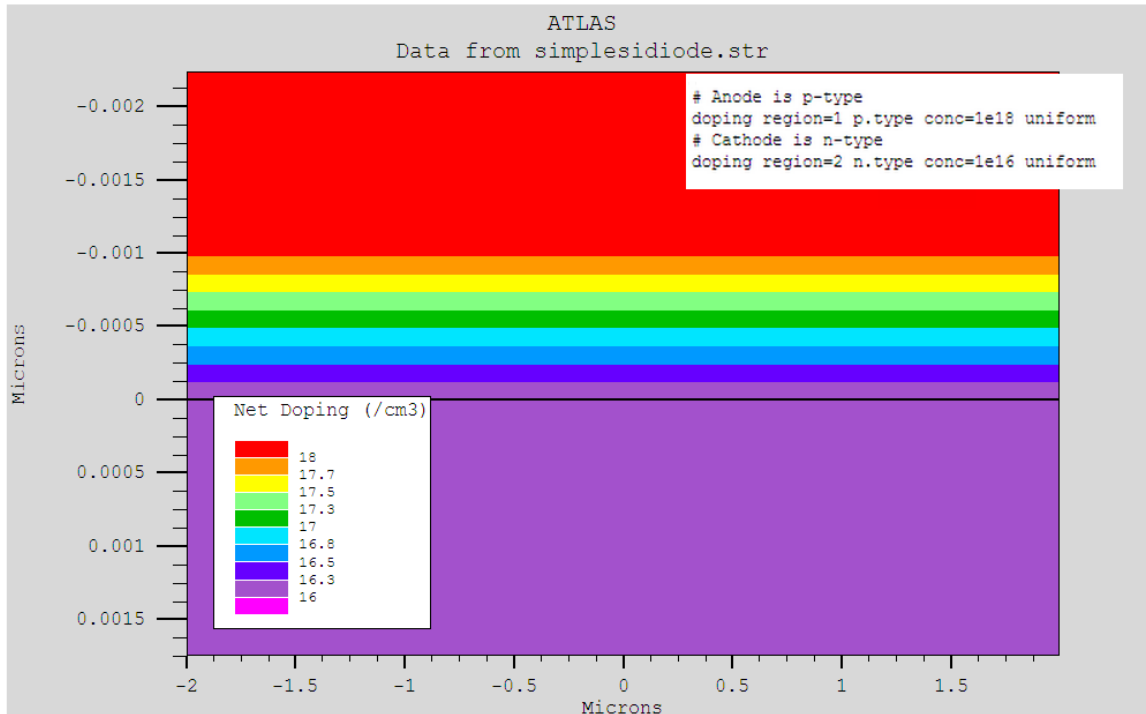


Figure 29. ATLAS doping profile of the junction of a simple Si pn diode.

To dope the device using a Gaussian profile requires more detail in the doping command. Here is a typical Gaussian doping profile command:

```
doping gaussian conc=1e18 characteristic = 0.02 p.type x.left=-2 x.right=2
peak=0.1
```

The concentration listed in the command will be the peak concentration and the characteristic is the standard deviation for which the doping level will drop off in a vertical direction [Ref. 1]. If the doping command did not take up the entire device in the horizontal direction the standard deviation in the laterally direction will be at 70% of the characteristic value. This ratio can be changed using the *ration.lateral* command [Ref. 1]. Figure 30 shows an example of Gaussian doping.

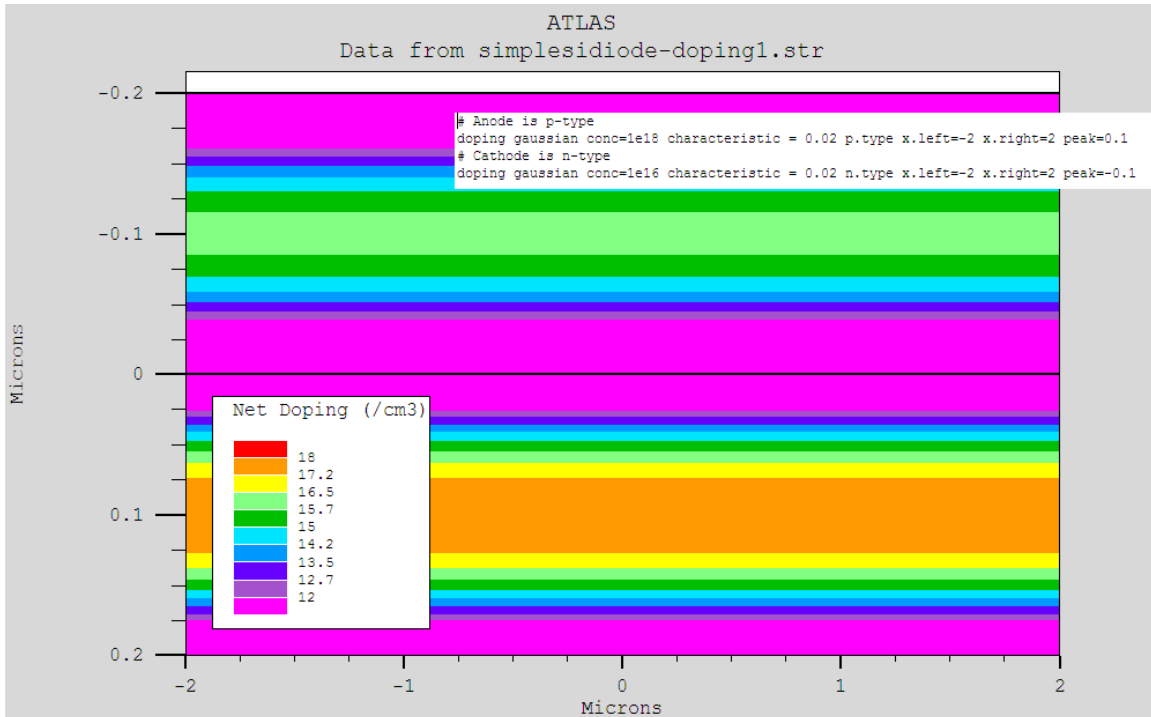


Figure 30. An example of Gaussian Doping distribution.

Silvaco has also given users the ability to define a custom doping profile in an ASCII file and use it to properly distribute the dopants in the device [Ref. 1].

#### 4. Material Models Specification

Once the designer has defined the structure and the geometry of the device being designed they can now change the default material properties and choose which models ATLAS will use to solve the devices electrical characteristics [Ref. 1]. The first of properties investigated will be the *contact* command. This command is used to tell ATLAS how to treat the electrode. In the default condition an electrode in contact is assumed to be ohmic [Ref. 1]. If the designer wants the electrode to be treated like a Schottky contact the design must use the *workfunction*. An example of this would be:

```
contact name=gate workfunction=4.8
```

This command would treat the contact as Schottky contact and set the contact named gate to 4.8eV [Ref. 1]. The designer can also use the contact command to change an electrode from being voltage controlled and make it current controlled. An example of this would be:

*contact name=drain current*

This would make the contact named drain a current controlled contact. ATLAS also has the ability to float contacts, short two contacts together, and make an open circuit contact. Since none of these features were used in this research they will not be discussed in detail.

The next step in the ATLAS design process is to designate material properties for the regions that are being used. ATLAS has an extensive library of different elements, compounds and alloys with their properties already defined [Ref. 1]. Silvaco allows the designer to edit these allows or create completely new materials. Some of the properties defined are bandgaps, mobility and absorption coefficients. An example of a way to use the material statement to improve the simulation is as follows:

*Material Material=Silicon EG300=1.12 mun=1100*

This command would set the bandgap and low field electron mobility for all the silicon in the device [Ref 1].

The next statement to investigate is the models statement. ATLAS has over seventy models that a designer can choose to use to improve the accuracy of the structure they are trying to simulate. These models would change the parameters of the device using the following command statements: *models, mobility, impact, and material* [Ref 1.] Figure 31 show an example of some of the mobility models available. For a list of all of ATLAS's models please refer to reference 1.

Model	Syntax	Notes
Concentration Dependent	CONMOB	Lookup table valid at 300K for Si and GaAs only. Uses simple power law temperature dependence.
Concentration and Temperature Dependent	ANALYTIC	Caughey-Thomas formula. Tuned for 77-450K.
Arora's Model	ARORA	Alternative to ANALYTIC for Si
Carrier-Carrier Scattering	CCSMOB	Dorkel-Leturq Model. Includes n, N and T dependence. Important when carrier concentration is high (e.g., forward bias power devices).
Parallel Electric Field Dependence	FLDMOB	Si and GaAs models. Required to model any type of velocity saturation effect.
Tasch Model	TASCH	Includes transverse field dependence. Only for planar devices. Needs very fine grid.
Watt Model	WATT	Transverse field model applied to surface nodes only.
Klaassen Model	KLA	Includes N, T, and n dependence. Applies separate mobility to majority and minority carriers. Recommended for bipolar devices
Shirahata Model	SHI	Includes N, $E_{\perp}$ . An alternative surface mobility model that can be combined with KLA.

Figure 31. Some of the mobility models available in ATLAS [After Ref. 1].

## 5. Numerical Method Selection

ATLAS allows several different methods for calculating the solution for semiconductor device problems [Ref. 1]. For each model type there are three types of solution techniques: decoupled, fully coupled and block. The designer should look and see what type of method the model they are using requires. Using the wrong method can lead to non-convergence or incorrect results. Silvaco has default settings that work for most cases [Ref. 1]

## 6 Solution Specifications

ATLAS will calculate AC, DC, small signal and transient solutions [Ref. 1]. Obtaining a solution is similar to setting up a test device. Once the command has been made the user will typically save the results using a log or save command. An example of solving a DC solution is given below:

```
solve vcathode=1.0
```



This will solve a single bias point with 1 volt on the cathode. The designer can also solve a sweeping bias using the following commands:

```
solve vcathode=0
```

```
solve vanode=-5 vfinal=5 vstep=0.1 name=anode
```

This will solve the circuit parameters by holding cathode voltage at 0 and sweeping the anode voltage from -5 to 5 with 0.1 voltage steps. If no solve voltage is designated Silvaco will put a default of 0 [Ref. 1]. The results can be saved to a log file by using the following command:

```
log outfile=simplesidiode-iv.log
```

This will save a log output file of the results from the voltage sweep in them.

## **7. Results Analysis**

The primary method when working with ATLAS to view the results of a simulation is using Tonyplot. Tonyplot is viewing program for ATLAS that allows the designer to view the structure and log files that are created by ATLAS. The structure files allow you to view the mesh diagram, doping concentrations, current densities, and other parameters. The log files allow you to view the results of ATLAS's electrical analysis in a graph format. It can show both log and linear scaling. It can also produce cylindrical graphs. Tonyplot has the ability to do cutlines to look at a specific slice of the device and see what is electrical occurring at the slice point or plane.

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## IV. TUNNEL JUNCTION MODELING

The ability to model and simulate tunnel junction diodes would greatly enhance the design ability of the multijunction solar cells. The ATLAS device simulator, by Silvaco International, has been proven to be an effective tool for modeling modern multijunction solar cells in research by A. Bates [Ref. 14] and P. Michalopoulos [Ref. 12]. Michalopoulos was able to produce a model to simulate a tunnel junction in his work in 2002 but since then researchers have been unable to reproduce this simulation [Ref. 12].

### A. SIMULATIONS

Several different simulation techniques in ATLAS were used to try to accurately simulate a tunnel junction. The research for this thesis started with looking at the work of past students that were simulating solar cells in Silvaco ATLAS. Earlier research in ATLAS had been successful in simulating a tunnel junction but, in recent years no researchers have been able to repeat this simulation. This thesis starts with early successful work by Michalopoulos [Ref. 12] and tries to either recreate his successful work or to produce another way to simulate a tunnel junction. During this research work from Michalopoulos [Ref. 12], Green [Ref. 15], Bates [Ref. 14], and Moore [Ref. 13] will be examined.

#### 1. Review and Modification of P. Michalopoulos Simulations

P. Michalopoulos in his thesis research in 2002 was the last known person to simulate a tunnel junction diode [Ref. 12]. The first simulation of this thesis starts by using Michalopoulos code and reviewing his results. Figure 32 shows an I-V curve for a InGaP tunnel junction that is from Michalopoulos June 2002 thesis [Ref. 12]. Michalopoulos designed this junction for use with a multijunction solar cell that he was attempting to simulate.

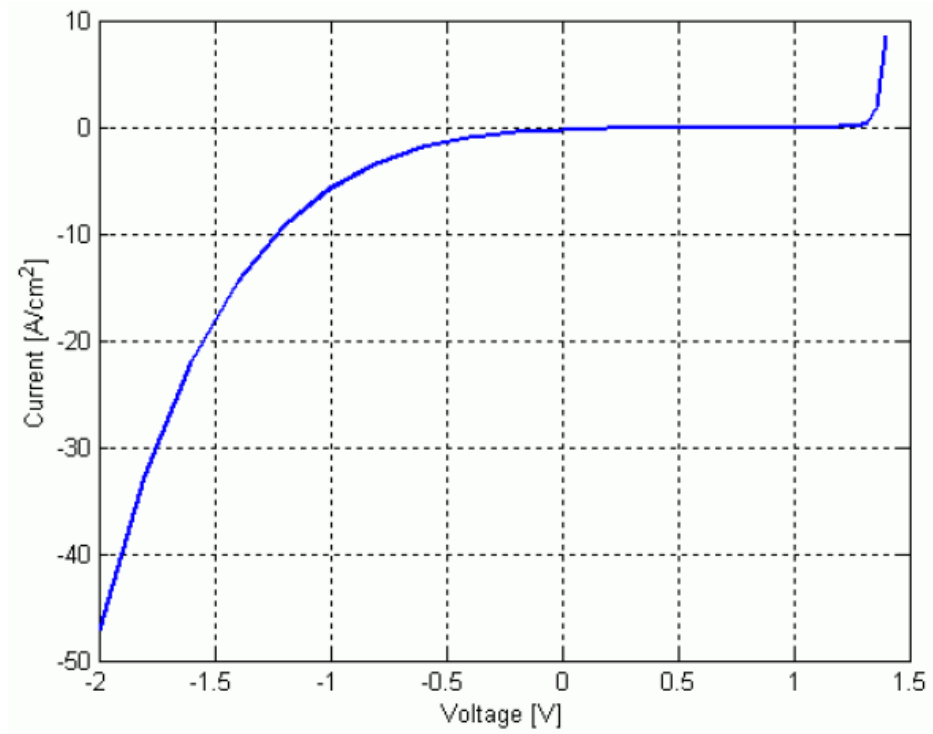


Figure 32. I-V curve for a InGaP tunnel junction [From Ref. 12]

When Michalopoulos code is loaded into Deckbuild and ran on the most current revision of Silvaco ATLAS software the results are significantly different. Figure 33 shows the results of running Michalopoulos code as he wrote it on the newest software.

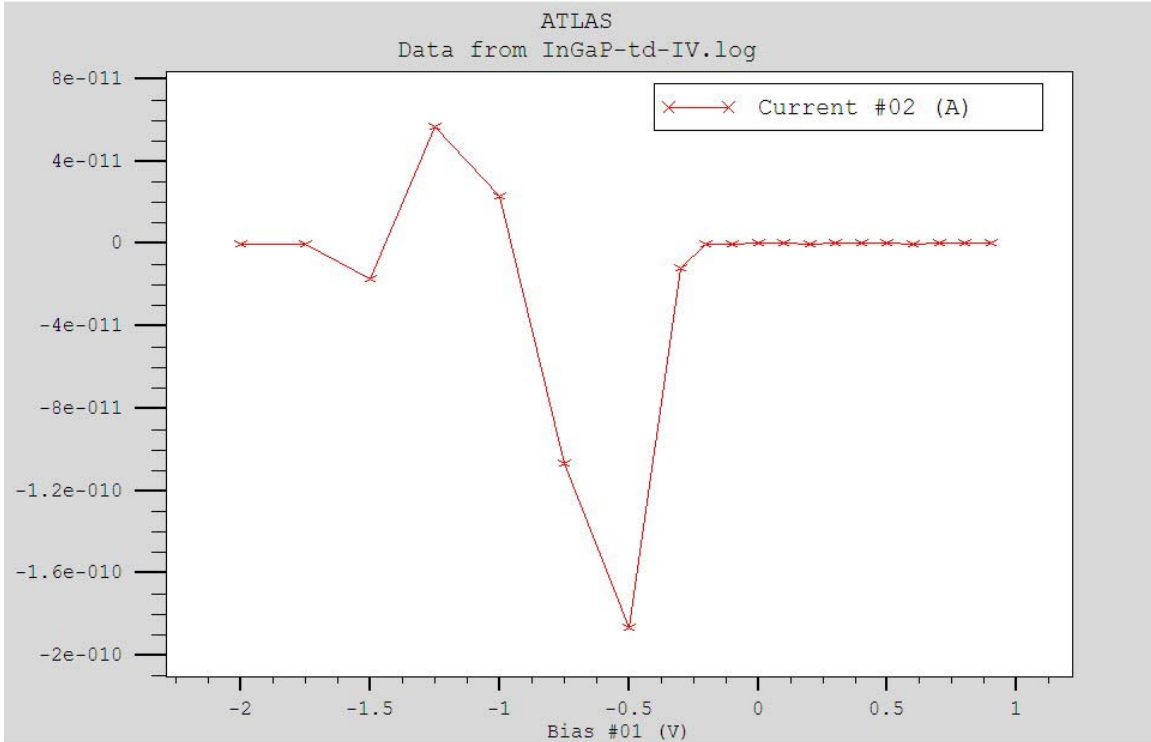


Figure 33. InGaP tunnel diode I-V using code from Reference 12.

With the new software his coding produced an erratic curve that did not resemble the original I-V curve. The first modification that was performed on his coding was to add additional calculation points to the simulation and try and produce a smoother curve. This resulted in a more erratic result with significantly smaller current. These results are shown in Figure 34.

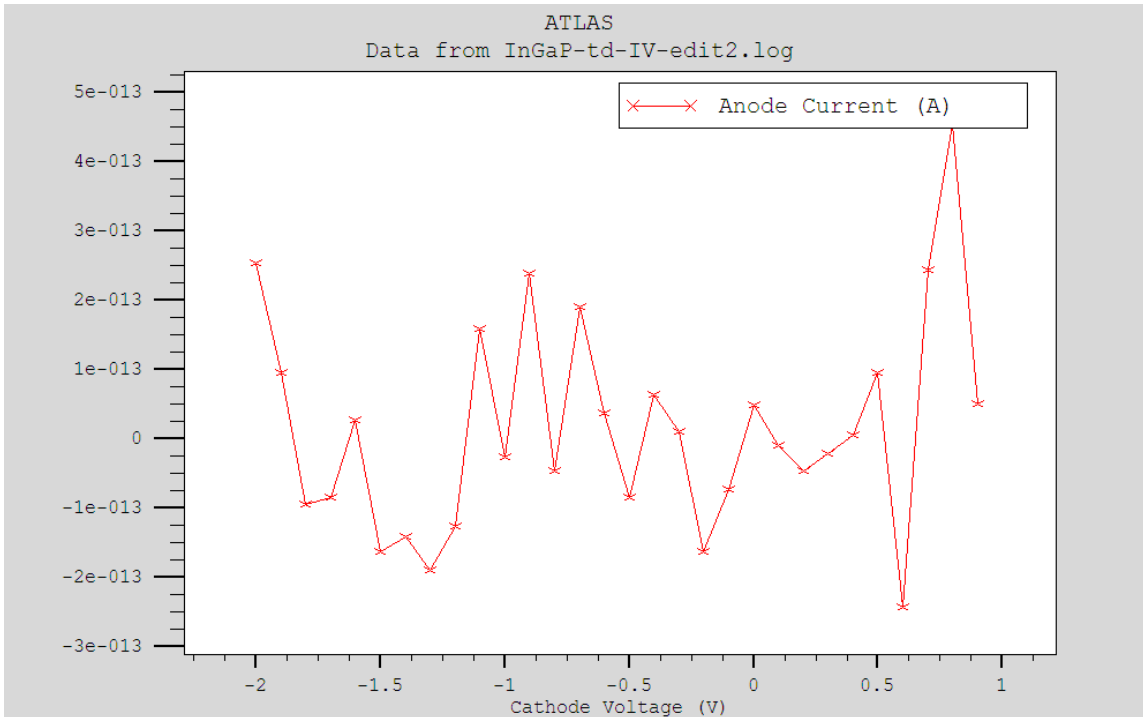


Figure 34. InGaP tunnel diode I-V curve using edit code from Reference 12

The next attempt to find the problem was to take his code and review each line. During this process the goal was to determine if there was a typo in his code or if some of his code was no longer valid when ran on the newer versions of Silvaco's software. During this examination of Michalopoulos coding no typing error were discovered but it was found that Michalopoulos was using a model that was no longer in use. He was using the TATUN model which was replaced with a newer TRAP.TUNNEL model [Ref. 16]. Once this model was replaced the coding was ran again. The results with the new model were very different. The new curve was smooth and consistent but did not accurately model the InGaP tunnel junction. This curve is shown in Figure 35.

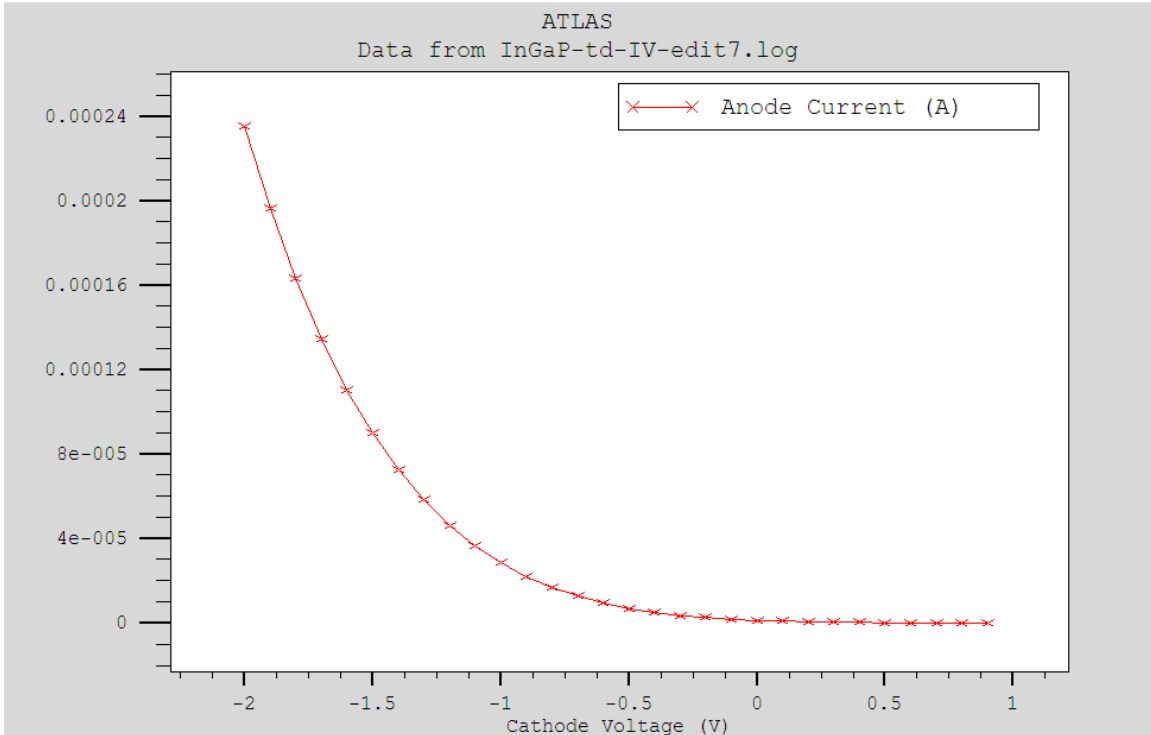


Figure 35. InGaP tunnel junction I-V curve using code from Reference 12 with new TRAP.TUNNEL model.

After examining the results it was decided that the best way to proceed was to try a different coding approach. Since many hours were spend trying to make Michalopoulous coding work it was decided that the best new approach was to start from scratch and write completely new coding. The final edit of Michalopoulous’s coding can be viewed in Appendix A.

## 2. Making a simple Silicon Tunnel Junction Diode

Since editing old code did not achieve the goal of producing an accurate model of a tunnel junction the new planned approach was to modify a simple working Si pn diode to make a new Silicon tunnel junction diode. The Si diode, before modification, produced an IV curve that resembled the IV curve of a normal forward biased Si diode. This IV curve can be seen in Figure 36 and the diodes code can be found in Appendix A.

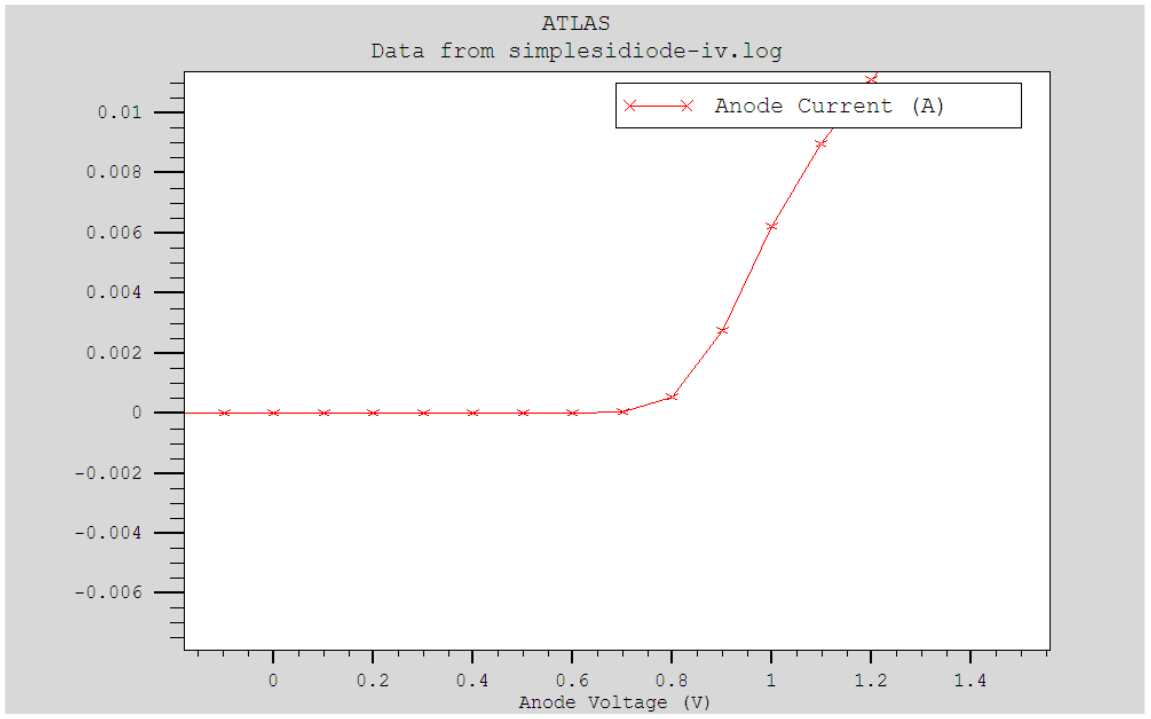


Figure 36. Simple Silicon diode forward biased IV curve.

The pn diode doping concentration was increased to simulate the new tunnel junction.  $N_D$  and  $N_A$  for the new diode were both  $1 \times 10^{20} \text{ cm}^{-3}$ . When the coding was run on ATLAS the resultant IV curve was similar in shape to a normal diode IV curve but with extremely high currents. Unfortunately it did not represent a tunnel diode IV. Figure 37 shows the IV curve of the Silicon tunnel diode and the ATLAS coding can be viewed in Appendix A.



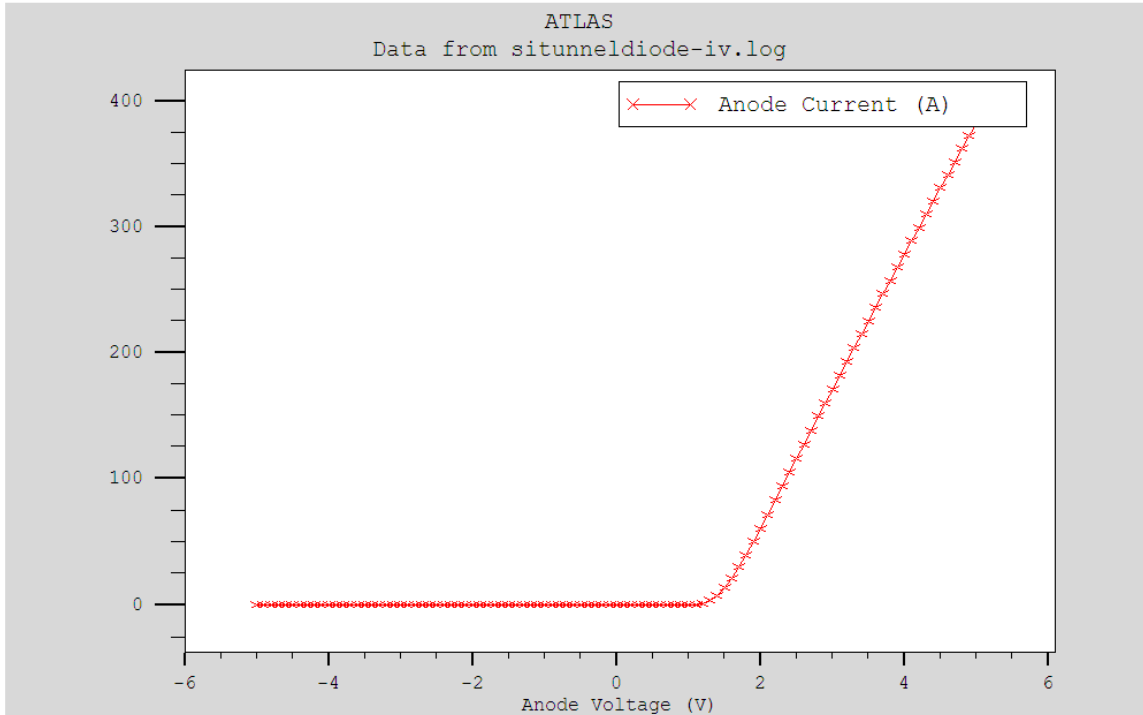


Figure 37. IV curve for Silicon tunnel junction diode.

Since the IV curve for the Si tunnel junction diode was representing a normal diode the next thing examined was the energy band diagrams of the simulated Si tunnel junction. First the band diagram was compared to the results from the simulation of a normal Si pn diode. The comparison can be seen in Figure 38. Referring to Figure 14, it can be seen that the band diagram of the tunnel junction in ATLAS looks similar in shape to the band diagram of a tunnel junction.

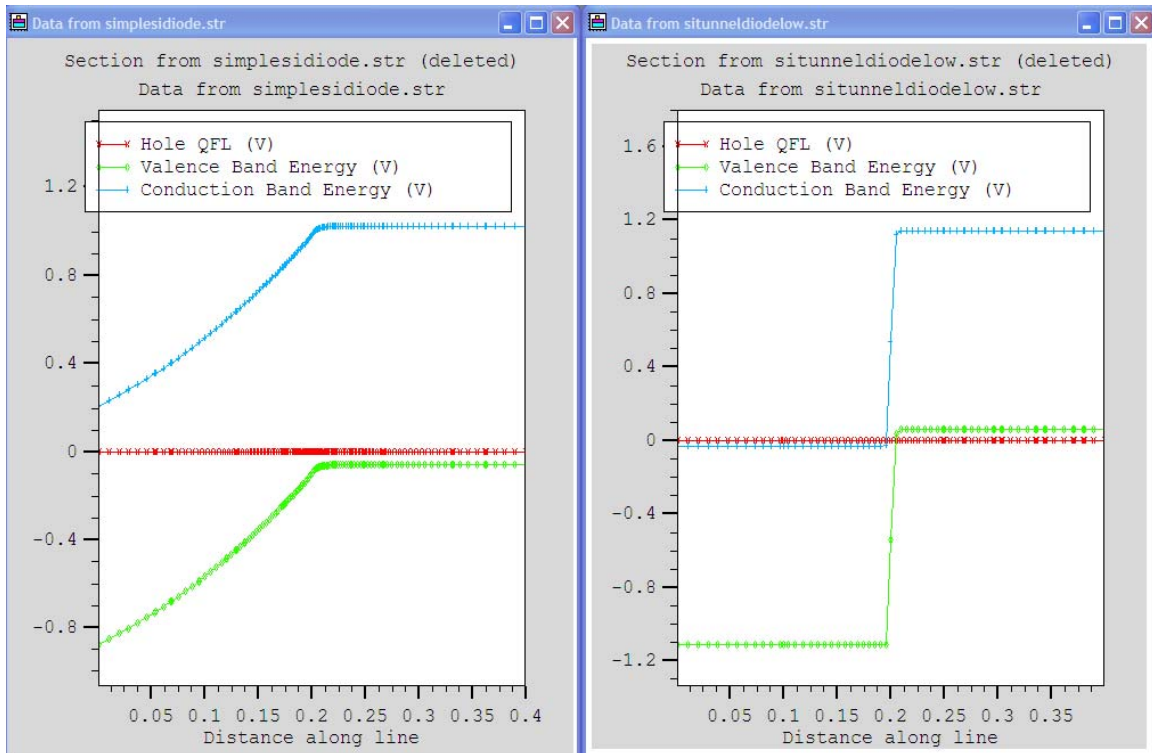


Figure 38. The band diagram of the simple Si diode on the left compared to the band diagram for Si tunnel junction doped at  $N_A$  and  $N_D=1e20$ .

The band diagram in Figure 38 was using a doping concentration of  $N_A$  and  $N_D=1e20$ . Since there is not very much overlap of energy states in the first tunnel junction diagram the simulation was run again with a doping concentration of  $N_A$  and  $N_D=1e25$ . When the doping concentration was increased the resultant IV curve was the same shape but the band diagram showed that more of the energy states should be inline. The new band diagram for the higher doping concentration is seen in Figure 39. Now the band diagram looks very similar to the desired band diagram but no tunneling is occurring.

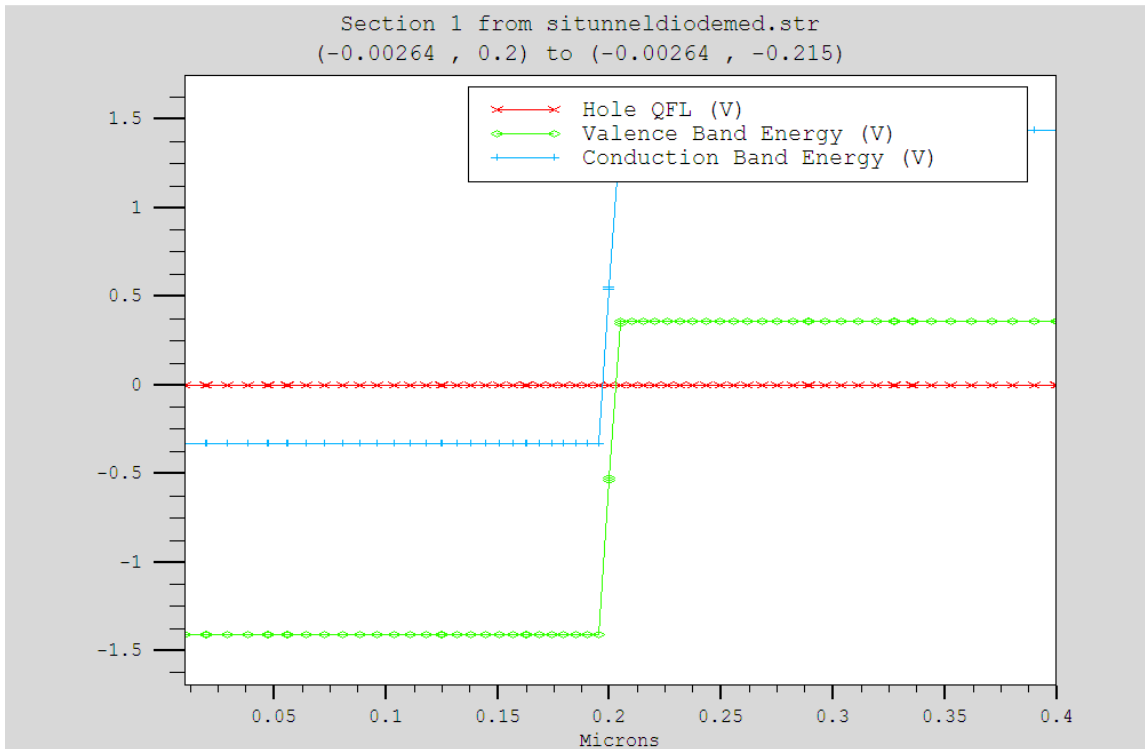


Figure 39. Band diagram of ATLAS simulated Si tunnel junction diode doped at  $N_A$  and  $N_D=1e25$

### 3. Ge Tunnel Diode

After the failure of the first two methods to produce an accurate tunnel junction simulation the next method attempted was to change the semiconductor material that was being simulated. The first step would be to make a simple Germanium diode and simulate it with ATLAS. This was relatively easy and produced a diode with a typical forward biased IV curve. This curve can be seen in Figure 40 and the coding for this diode can be viewed in Appendix A.

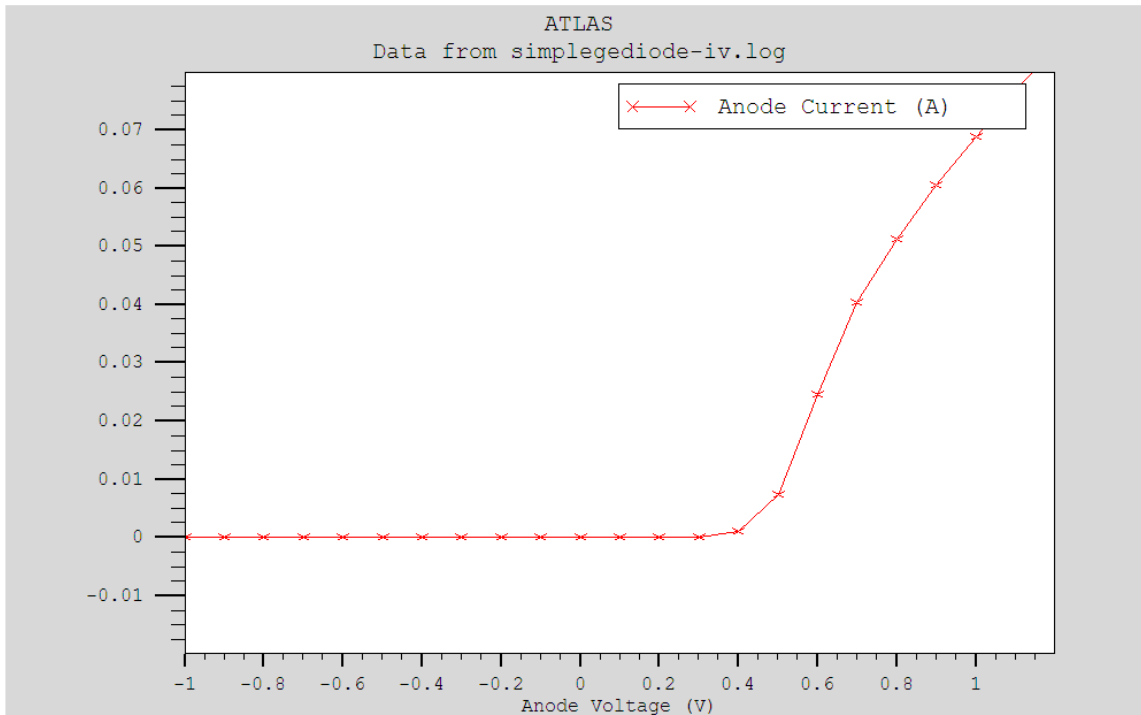


Figure 40. IV curve for a Ge forward biased diode.

The next step in designing the Ge tunnel diode was to modify the code to reflect concentrations that would produce tunneling conditions. For the Ge tunnel diode simulation  $N_D = 1 \times 10^{25}$  and  $N_A = 1 \times 10^{25}$  and a tunnel interfacing command was entered help produce the desired results. The resultant IV curve did not resemble a tunnel junction IV curve. It was similar to the Ge forward biased diode but with extremely higher current levels. The resultant band diagram again looks like a typical Ge tunnel junction with very steep valance and conduction band curves. The Silvaco program will still not cause the tunneling phenomenon to occur in the device. Figure 41 shows the resultant IV curve and the band diagram can be seen in Figure 42. After repeated failure the next method was to review the work of Dave Moore who was successful in simulating a thyristor using Silvaco's ATLAS software which has a negative resistance area like the tunnel junction [Ref. 13].

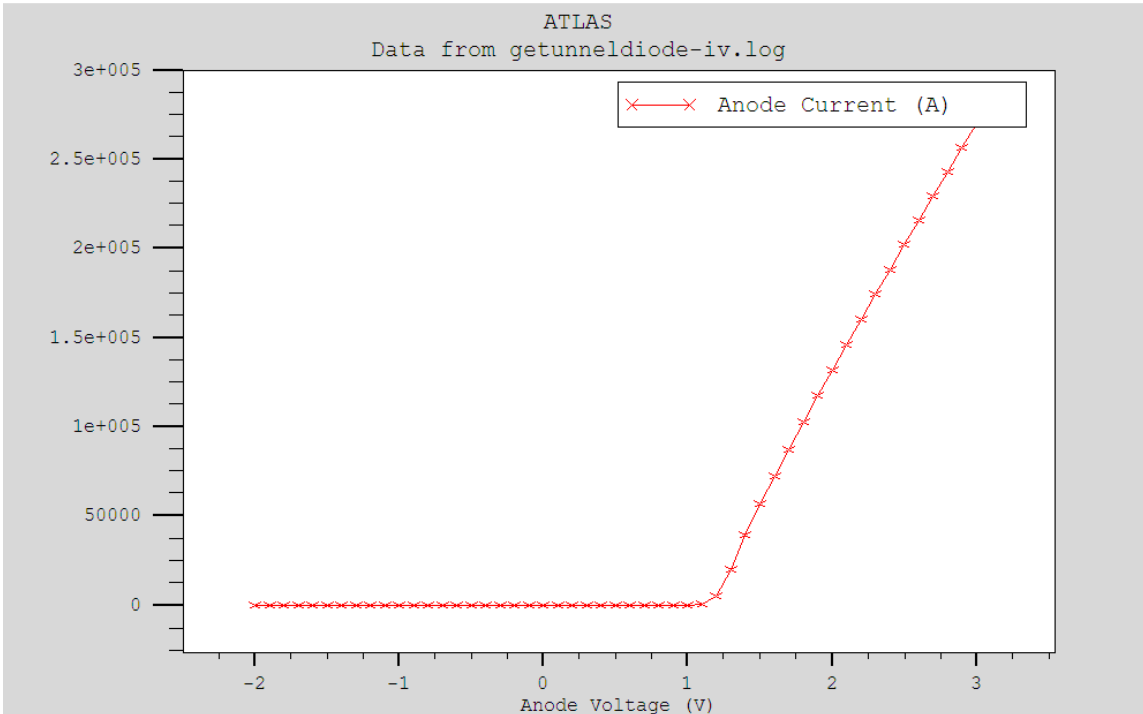


Figure 41. IV curve for Ge Tunnel Diode.

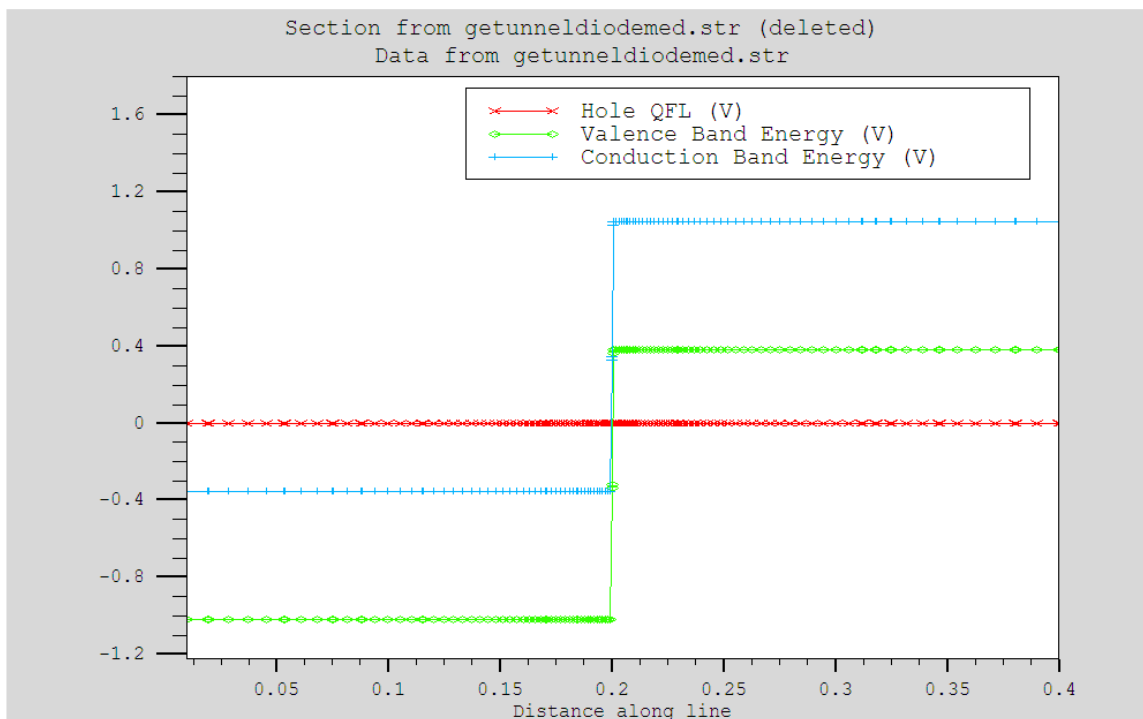


Figure 42. Band diagram of a Ge tunnel junction doped with  $N_A$  and  $N_D=1e25$

#### 4. Review of D. Moore's Thyristor Simulation [Ref. 13]

Dave Moore in his thesis, in the summer 2005, simulated a thyristor using Silvaco's ATLAS software [Ref. 13]. In his simulations he was able to produce an accurate IV curve for his thyristor device. He then tried several different doping levels to see their effects on his simulation of the thyristor. His results for his different doping levels of the P1 region of his device are shown in Figure 43 [Ref. 13].

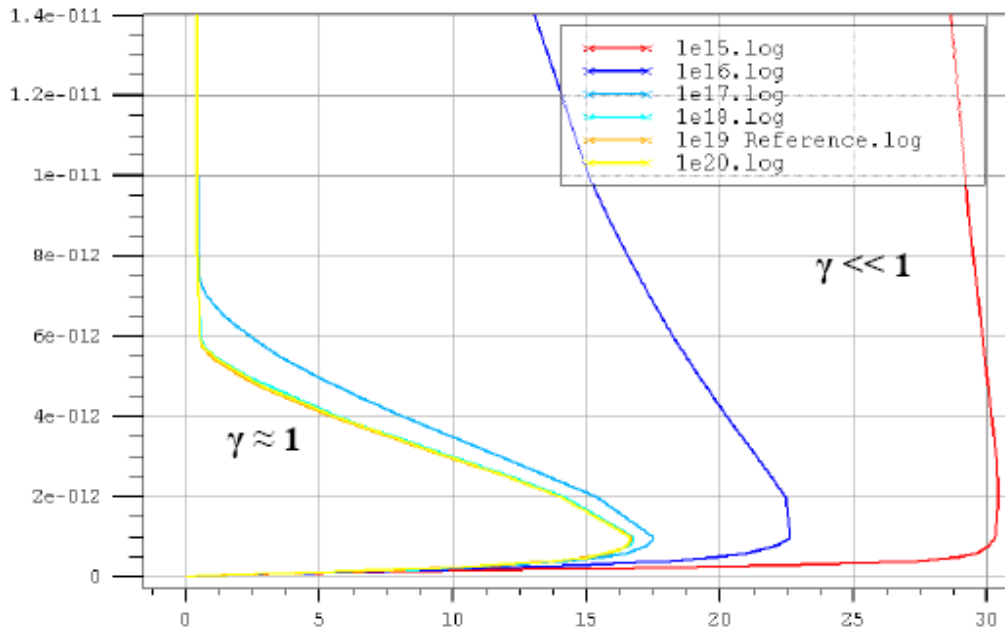


Figure 43. Moore's Thyristor's IV curves for different doping levels of the P1 [From Ref. 13]

The goal was to use his coding and try to first recreate his results and then use what was learned from his programming to create a tunnel junction device. This coding for the thyristor was extremely detailed and required an unusual amount of processing time. Once his coding was processed by ATLAS the results were disappointing. Again the result returned did not match what was shown in his work. Figure 44 shows the IV curve received when running his coding with a P1 doping of 4e19. His coding can be reviewed in Appendix A or in reference 13.

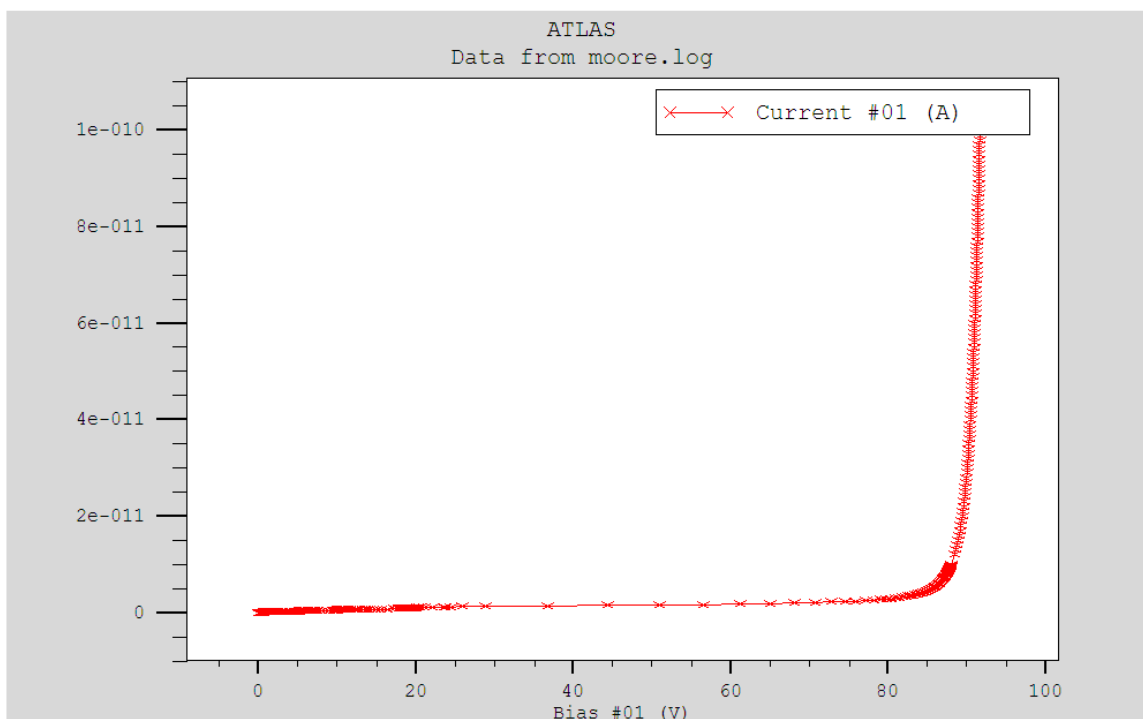


Figure 44. Thyristor IV curve using coding from Reference 13.

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## V. CONCLUSIONS AND RECOMMENDATIONS

This thesis has conducted a detailed look at the operation of the tunnel diode and the possibility of simulating it using Silvaco's ATLAS software. Even though the end result of producing a working model of a tunnel junction for use in solar cell design was not accomplished, significant progress was made in learning more about how Silvaco simulates devices. Given Silvaco's ATLAS software's extensive ability to model semiconductor materials the potential to fully model a multijunction device definitely exists.

This thesis was a continuation of research into effective methods of modeling multijunction solar cells. Silvaco International's ATLAS has proven to be a powerful modeling tool with the possibility of greatly enhancing the design process for solar devices. More research should be performed on modeling the entire device and improving the model of each component. By investigating each component of the device the designer will be able to break the design process into smaller parts that are more easily solved. Once each component of the device is modeled correctly connecting the parts to make a better overall model can be done.

When further research is performed on simulating a tunnel junction device in ATLAS the following recommendations are given. First, dedicate the majority of the early work time to fully understanding how Silvaco's ATLAS models any type of semiconductor device. Second, use Silvaco's different model statement to attempt to make tunneling actually occur through the device. Since the band diagram of the device looks correct, Silvaco is just not performing the tunneling phenomenon. Next, when attempting to model an unusual device investigate all the model statements that are practical. When first programming these one line model statements appear to be only for fine tuning results but they have a much larger effect. Lastly, when attempting to model a tunnel junction device, review the past work done by Moore [Ref. 13] and Michalopoulos [Ref. 12].

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## APPENDIX A. ATLAS INPUT DECKS

### A. DECKBUILD CODING FOR ATLAS

Given in the following appendix is the coding used to do the simulations that were performed during this thesis. Professor Sherif Michael of the Naval Postgraduate Schools, Electrical and Computer Engineering department will have these codes and others in a digital format.

#### 1. Simple Silicon PN Junction Diode

```
go atlas

mesh space.mult=1

x.mesh loc=-2 spac=0.1
x.mesh loc=2 spac=0.1

y.mesh loc=-0.2 spac=0.01
y.mesh loc=0 spac=0.001
y.mesh loc=0.2 spac=0.01

# Anode
region num=1 material=Si x.min=-2 x.max=2 y.min=-0.2 y.max=0
# Cathode
region num=2 material=Si x.min=-2 x.max=2 y.min=0 y.max=0.2

# Electrodes
electrode name=anode top
electrode name=cathode bottom

# Anode is p-type
doping region=1 p.type conc=1e18 uniform
# Cathode is n-type
doping region=2 n.type conc=1e16 uniform

struct outfile=simplesidiode.str
tonyplot simplesidiode.str

models bbt.kl trap.tunnel

solve init
log outfile=simplesidiode-iv.log
solve vanode=-5 vfinal=5 vstep=0.1 name=anode
tonyplot simplesidiode-iv.log
```

quit

## 2. InGaP Tunnel Diode [After Ref. 12]

go atlas

#InGaP tunnel diode originally created by P. Michalopoulos  
#Edited for this thesis by Robert J. Gelinas

#Mesh

mesh space.mult=1

# X-Mesh: surface=500  $\mu\text{m}^2 = 1/200,000 \text{ cm}^2$

x.mesh loc=-250 spac=50

x.mesh loc=0 spac=10

x.mesh loc=250 spac=50

# Y-Mesh

y.mesh loc=-0.18 spac=0.002

# Tunnel emitter (0.015  $\mu\text{m}$ )

y.mesh loc=-0.165 spac=0.002

# Tunnel base (0.015  $\mu\text{m}$ )

y.mesh loc=-0.15 spac=0.001

# Regions

# Tunnel emitter

region num=1 material=InGaP x.min=-250 x.max=250 y.min=-0.18 y.max=-0.165

# Tunnel base

region num=2 material=InGaP x.min=-250 x.max=250 y.min=-0.165 y.max=-0.15

# Electrodes

electrode name=cathode x.min=-250 x.max=250 y.min=-0.18 y.max=-0.18

electrode name=anode x.min=-250 x.max=250 y.min=-0.15 y.max=-0.15

# Doping

# Tunnel emitter

doping uniform region=1 p.type conc=8e18

# Tunnel base

doping uniform region=2 n.type conc=1e19

# Material properties

material TAUN=1e-7 TAUP=1e-7 COPT=1.5e-10 AUGN=8.3e-32 AUGP=1.8e-31

```

# Vacuum
material material=Vacuum real.index=3.3 imag.index=0

# GaAs
material material=GaAs EG300=1.42 PERMITTIVITY=13.1 AFFINITY=4.07
material material=GaAs MUN=8800 MUP=400
material material=GaAs NC300=4.7e17 NV300=7e18
material material=GaAs index.file=GaAs.opt

# InGaP
material material=InGaP EG300=1.9 PERMITTIVITY=11.62 AFFINITY=4.16
material material=InGaP MUN=1945 MUP=141
material material=InGaP NC300=1.3e20 NV300=1.28e19
material material=InGaP index.file=InGaP.opt

# AlInP (=InAsP)
material material=InAsP EG300=2.4 PERMITTIVITY=11.7 AFFINITY=4.2
material material=InAsP MUN=2291 MUP=142
material material=InAsP NC300=1.08e20 NV300=1.28e19
material material=InAsP index.file=InGaP.opt

# Models
models BBT.KL
MODEL TRAP.TUNNEL

# Solving
solve init

solve vcathode=0
solve vcathode=-0.25
solve vcathode=-0.5
solve vcathode=-0.75
solve vcathode=-1
solve vcathode=-1.25
solve vcathode=-1.5

log outfile=InGaP-td-IV-edit7.log
solve vcathode=-2
solve vcathode=-1.90
solve vcathode=-1.80
solve vcathode=-1.70
solve vcathode=-1.60
solve vcathode=-1.5
solve vcathode=-1.40
solve vcathode=-1.30

```

```
solve vcathode=-1.20
solve vcathode=-1.10
solve vcathode=-1
solve vcathode=-0.90
solve vcathode=-0.80
solve vcathode=-0.70
solve vcathode=-0.60
solve vcathode=-0.5
solve vcathode=-0.40
solve vcathode=-0.3
solve vcathode=-0.2
solve vcathode=-0.1
solve vcathode=0
solve vcathode=0.1
solve vcathode=0.2
solve vcathode=0.3
solve vcathode=0.4
solve vcathode=0.5
solve vcathode=0.6
solve vcathode=0.7
solve vcathode=0.8
solve vcathode=0.9
```

```
quit
```

### 3. Silicon Tunnel Junction Diode

```
go atlas
```

```
#Simple Si tunnel diode
#Created by Robert J. Gelinias
```

```
mesh space.mult=1
```

```
x.mesh loc=-2 spac=0.2
x.mesh loc=2 spac=0.2
```

```
y.mesh loc=-0.2 spac=0.01
y.mesh loc=0 spac=0.005
y.mesh loc=0.2 spac=0.01
```

```
# Anode
```

```
region num=1 material=Si x.min=-2 x.max=2 y.min=-0.2 y.max=0
```

```
# Cathode
```

```
region num=2 material=Si x.min=-2 x.max=2 y.min=0 y.max=0.2
```

```

# Electrodes
electrode name=anode top
electrode name=cathode bottom

interface tunnel thermionic x.min=-2 x.max=2 y.min=-0.2 y.max=0.2

# Anode is p-type
doping region=1 p.type conc=1e20 uniform
# Cathode is n-type
doping region=2 n.type conc=1e20 uniform

output van.band con.band qfp qfn qss

models bbt.kl trap.tunnel

solve init

save outf=situnneldiode.str
tonyplot situnneldiode.str

log outfile=situnneldiode-iv.log
solve vanode=-5 vfinal=5 vstep=0.1 name=anode
tonyplot situnneldiode-iv.log

quit

```

#### **4. Simple Ge pn Diode.**

```

go atlas

#Simple Ge Diode
#Created by Robert J. Gelinias

mesh space.mult=1

x.mesh loc=-2 spac=0.1
x.mesh loc=2 spac=0.1

y.mesh loc=-0.2 spac=0.01
y.mesh loc=0 spac=0.001
y.mesh loc=0.2 spac=0.01

# Anode

```

```

region num=1 material=Ge x.min=-2 x.max=2 y.min=-0.2 y.max=0
# Cathode
region num=2 material=Ge x.min=-2 x.max=2 y.min=0 y.max=0.2

# Electrodes
electrode name=anode top
electrode name=cathode bottom

# Anode is p-type
doping region=1 p.type conc=2e18 uniform
# Cathode is n-type
doping region=2 n.type conc=1e16 uniform

struct outfile=simplegediode.str
tonyplot simplegediode.str

models bbt.kl trap.tunnel

solve init
log outfile=simplegediode-iv.log
solve vanode=-3 vfinal=3 vstep=0.1 name=anode
tonyplot simplegediode-iv.log

quit

```

## 5. Ge Tunnel Junction Diode

```

go atlas

#Ge Tunnel Diode
#Created by Robert J. Gelinias

mesh space.mult=1

x.mesh loc=-2 spac=0.1
x.mesh loc=2 spac=0.1

y.mesh loc=-0.2 spac=0.01
y.mesh loc=0 spac=0.001
y.mesh loc=0.2 spac=0.01

# Anode
region num=1 material=Ge x.min=-2 x.max=2 y.min=-0.2 y.max=0
# Cathode
region num=2 material=Ge x.min=-2 x.max=2 y.min=0 y.max=0.2

# Electrodes

```



```

electrode name=anode top
electrode name=cathode bottom

interface tunnel thermionic x.min=-2 x.max=2 y.min=-0.2 y.max=0.2

# Anode is p-type
doping region=1 p.type conc=2e24 uniform
# Cathode is n-type
doping region=2 n.type conc=4e21 uniform

output val.band con.band qfp qfn qss

models bbt.kl trap.tunnel

solve init

save outf=gettunnelodiode.str
tonyplot gettunnelodiode.str

log outfile=gettunnelodiode-iv.log
solve vanode=-2 vfinal=3 vstep=0.1 name=anode
tonyplot gettunnelodiode-iv.log

quit

```

## 6. Thyristor coding by Dave Moore [From Ref. 13]

GO ATLAS

```

# Sets variable used in input the doping concentrations for the thyristor layers
SET P1_DOPING=4.0e19
SET N1_DOPING=7.0e15
SET P2_DOPING=2.0e16
SET N2_DOPING=4.0e19

# Defines variables to be used to define to corners of the various layers
SET X01=07.2
SET X02=09.2
SET X03=11.2
SET X04=12.8
SET X05=16.8
SET X06=20.0
SET X07=20.0
SET X08=22.0
SET X09=26.8
SET X10=28.4

```

```
SET X11=30.8
SET X12=34.8
SET X13=37.2
SET X14=38.8
SET X15=40.4
SET X16=42.8
SET X17=50.0
SET Y01=0.3
SET Y02=02.0
SET Y03=04.0
```

```
# Defines the mesh used carry out the numerical solution by ATLAS.
```

```
MESH
```

```
X.MESH LOC=0.0 SPACING=1
X.MESH LOC=$X01 SPACING=0.5
X.MESH LOC=$X02 SPACING=0.5
X.MESH LOC=$X03 SPACING=0.2
X.MESH LOC=$X04 SPACING=0.1
X.MESH LOC=$X05 SPACING=0.05
X.MESH LOC=$X07 SPACING=0.05
X.MESH LOC=$X08 SPACING=0.05
X.MESH LOC=$X09 SPACING=0.1
X.MESH LOC=$X10 SPACING=0.25
X.MESH LOC=$X11 SPACING=0.5
X.MESH LOC=$X12 SPACING=0.5
X.MESH LOC=$X13 SPACING=0.5
X.MESH LOC=$X14 SPACING=0.5
X.MESH LOC=$X15 SPACING=0.5
X.MESH LOC=$X16 SPACING=0.75
X.MESH LOC=$X17 SPACING=1.0
Y.MESH LOC=0.0 SPACING=0.05
Y.MESH LOC=$Y01 SPACING=0.05
Y.MESH LOC=1.0 SPACING=0.1
Y.MESH LOC=2.25 SPACING=0.25
Y.MESH LOC=$Y03 SPACING=0.5
```

```
# Reduces mesh density in non-critical areas to speed up simulation
```

```
ELIMINATE Y.DIR Y.MIN=2.25 Y.MAX=$Y03 X.MIN=0 X.MAX=$X17
ELIMINATE Y.DIR Y.MIN=0.5 Y.MAX=2 X.MIN=0 X.MIN=14
ELIMINATE Y.DIR Y.MIN=2.5 Y.MAX=3.75 X.MIN=10 X.MAX=25
```

```
# Defines the regions in ATLAS, which are equivalent to the layers in a thyristor.
```

```
# Region 1 is the N1 layer
# Region 2 is the P1 layer
# Region 3 is the P2 layer
# Region 4 is the N2 layer
```

```
REGION NUMBER=1 MATERIAL=SILICON
REGION NUMBER=2 MATERIAL=SILICON Y.MIN=0 Y.MAX=$Y01
X.MIN=$X02 X.MAX=$X05
REGION NUMBER=3 MATERIAL=SILICON Y.MIN=0 Y.MAX=$Y02
X.MIN=$X07 X.MAX=$X16
REGION NUMBER=4 MATERIAL=SILICON Y.MIN=0 Y.MAX=$Y01
X.MIN=$X08 X.MAX=$X11
REGION NUMBER=5 MATERIAL=SILICON Y.MIN=0 Y.MAX=$Y01
X.MIN=$X12 X.MAX=$X15
```

```
# Defines the location of the contacts to certain layers
ELECTRODE NAME=anode TOP X.MIN=$X03 X.MAX=$X04
ELECTRODE NAME=cathode X.MIN=$X09 X.MAX=$X10
ELECTRODE NAME=gate X.MIN=$X13 X.MAX=$X14
```

```
# Defines the doping profile of the layers
DOPING UNIFORM N.TYPE REGION=1 CONCENTRATION=$N1_DOPING
DOPING UNIFORM P.TYPE REGION=2 CONCENTRATION=$P1_DOPING
DOPING UNIFORM P.TYPE REGION=3 CONCENTRATION=$P2_DOPING
DOPING UNIFORM N.TYPE REGION=4 CONCENTRATION=$N2_DOPING
DOPING UNIFORM P.TYPE REGION=5 CONCENTRATION=$P1_DOPING
```

```
#Refines the grid in areas with rapid changes in doping with distance
REGRID DOPING LOG RATIO=2 SMOOTH=4 X.MIN=$X04 X.MAX=$X09
Y.MIN=0 Y.MAX=$Y02
SOLVE INIT
```

```
# Saves and plots the structure file
save outf=moore.str
tonyplot moore.str
```

```
# Defines the mobility and recombination models used for this simulation
MODEL BIPOLAR FERMI
```

```
# Specifies that this simulation will be controlled by current through the anode
CONTACT name=anode current
```

```
# Specifies the numerical technique used
METHOD NEWTON
```

```
# Opens the output file to store data generated by the following set of solution
points
LOG OUTFILE=moore.log
```

```
# Specifies the current levels where solutions are required
SOLVE INIT
```

```
solve ianode=1e-19
solve ianode=1.2e-19
solve ianode=1.4e-19
solve ianode=1.6e-19
solve ianode=2e-19
solve ianode=4e-19
solve ianode=1e-18
solve ianode=1e-17
solve ianode=2e-17
solve ianode=4e-17
solve ianode=7e-17
solve ianode=1.0e-16 istep=.2e-16 ifinal=1e-15 name=anode
solve ianode=1.2e-15 istep=0.1e-15 ifinal=1e-14 name=anode
solve ianode=1.2e-14 istep=0.1e-14 ifinal=1e-13 name=anode
solve ianode=1.2e-13 istep=0.1e-13 ifinal=1e-12 name=anode
solve ianode=1.2e-12 istep=0.1e-12 ifinal=1e-11 name=anode
solve ianode=1.2e-11 istep=0.1e-11 ifinal=1e-10 name=anode

# Plots the IV curve
tonyplot moore.log

quit
```

## APPENDIX B. RUNTIME OUTPUTS

### A. DECKBUILD RUNTIME OUTPUTS FROM ATLAS

The Runtime Outputs files are displayed in Deckbuild upon completion of a simulation. These files show the results of every calculation of ATLAS and can provide insight to why a program is not running correctly. The output files are very detail and therefore they can sometimes be very long. Do to the length of these files this thesis will only include the results for the three tunnel diode simulations.

#### 1. InGaP Tunnel Diode [After Ref. 12]

```
ATLAS> #InGaP tunnel diode originally created by P. Michalopoulos
ATLAS> #Edited for this thesis by Robert J. Gelinas
ATLAS> #Mesh
ATLAS> mesh space.mult=1
ATLAS> # X-Mesh: surface=500 um2 = 1/200,000 cm2
ATLAS> x.mesh loc=-250 spac=50
ATLAS> x.mesh loc=0 spac=10
ATLAS> x.mesh loc=250 spac=50
ATLAS> # Y-Mesh
ATLAS> y.mesh loc=-0.18 spac=0.002
ATLAS> # Tunnel emitter (0.015 um)
ATLAS> y.mesh loc=-0.165 spac=0.002
ATLAS> # Tunnel base (0.015 um)
ATLAS> y.mesh loc=-0.15 spac=0.001
ATLAS> # Regions
ATLAS> # Tunnel emitter
ATLAS> region num=1 material=InGaP x.min=-250 x.max=250 y.min=-0.18
y.max=-0.165
ATLAS> # Tunnel base
ATLAS> region num=2 material=InGaP x.min=-250 x.max=250 y.min=-0.165
y.max=-0.15
ATLAS> # Electrodes
ATLAS> electrode name=cathode x.min=-250 x.max=250 y.min=-0.18 y.max=-
0.18
```

```
Electrode # 1
Name: cathode
Number of boundary nodes: 21
Dimensions in microns:
    min    max
x -2.500e+002 2.500e+002
```

y -1.800e-001 -1.800e-001

ATLAS> electrode name=anode x.min=-250 x.max=250 y.min=-0.15 y.max=-0.15

Electrode # 2

Name: anode

Number of boundary nodes: 21

Dimensions in microns:

	min	max
x	-2.500e+002	2.500e+002
y	-1.500e-001	-1.500e-001

ATLAS> # Doping

ATLAS> # Tunnel emitter

ATLAS> doping uniform region=1 p.type conc=8e18

Mesh

Type: non-cylindrical

Total grid points: 399

Total triangles: 720

Obtuse triangles: 0 (0 %)

ATLAS> # Tunnel base

ATLAS> doping uniform region=2 n.type conc=1e19

ATLAS> # Material properties

ATLAS> material TAUN=1e-7 TAUP=1e-7 COPT=1.5e-10 AUGN=8.3e-32  
AUGP=1.8e-31

ATLAS> # Vacuum

ATLAS> material material=Vacuum real.index=3.3 imag.index=0

ATLAS> # GaAs

ATLAS> material material=GaAs EG300=1.42 PERMITTIVITY=13.1  
AFFINITY=4.07

ATLAS> material material=GaAs MUN=8800 MUP=400

ATLAS> material material=GaAs NC300=4.7e17 NV300=7e18

ATLAS> material material=GaAs index.file=GaAs.opt

ATLAS> # InGaP

ATLAS> material material=InGaP EG300=1.9 PERMITTIVITY=11.62  
AFFINITY=4.16

ATLAS> material material=InGaP MUN=1945 MUP=141

ATLAS> material material=InGaP NC300=1.3e20 NV300=1.28e19

ATLAS> material material=InGaP index.file=InGaP.opt

ATLAS> # AllInP (=InAsP)

ATLAS> material material=InAsP EG300=2.4 PERMITTIVITY=11.7  
AFFINITY=4.2

ATLAS> material material=InAsP MUN=2291 MUP=142

ATLAS> material material=InAsP NC300=1.08e20 NV300=1.28e19

ATLAS> material material=InAsP index.file=InGaP.opt

```

ATLAS> # Models
ATLAS> models BBT.KL
ATLAS> MODEL TRAP.TUNNEL
ATLAS> # Solving
ATLAS> solve init

```

Starting: BLAZE module.

Obtaining static solution:

```

init      psi  psi
direct    x   rhs
  i  j  m -5.00* -26.0*
-----
  1  1  G -0.221 -11.34
  2  1  G -0.274 -11.40
  3  1  G -0.544 -11.46
  4  1  G -0.653 -11.53
  5  1  G -0.753 -11.61
  6  1  G -0.824 -11.71
  7  1  G -1.075 -11.84
  8  1  G -1.037 -12.10
  9  1  G -1.233 -12.52
 10  1  G -14.1* -26.2*

```

ATLAS> solve vcathode=0

Obtaining static solution:

```

prev      psi  n  p  psi  n  p
direct    x  x  x  rhs  rhs  rhs
  i  j  m -5.00* -5.00* -5.00* -26.0* -17.3* -17.3*
-----
  1  N -7.43* -4.947 -3.765 -27.0* -12.72 -13.19
  2  N -13.4* -13.8* -13.3* -27.1* -12.83 -13.28

```

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
cathode	0.000e+000	8.464e-017	-1.066e-006	-1.066e-006	-1.066e-006
anode	0.000e+000	1.066e-006	-4.104e-016	1.066e-006	1.066e-006
Total					-1.734e-013

Time for bias point: 0.39 sec.

Total time: 2.69 sec.

ATLAS> solve vcathode=-0.25

Obtaining static solution:

V( cathode ) = -0.25

```
prev      psi  n  p  psi  n  p
direct    x  x  x  rhs  rhs  rhs
i  j  m -5.00* -5.00* -5.00* -26.0* -17.3* -17.3*
```

```
-----
1  N  0.962 -0.115 -0.143 -14.85  1.272  0.564
2  N -0.841 -0.098 -0.074 -26.9* -0.460 -0.983
3  N -2.232 -1.922 -1.959 -26.9* -4.800 -3.879
4  N -5.09* -5.38* -4.924 -26.8* -10.93 -9.647
5  N -10.8* -11.4* -10.6* -26.8* -12.63 -13.43
```

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
cathode	-2.500e-001	1.234e-016	-2.907e-006	-2.907e-006	-2.907e-006
anode	0.000e+000	2.907e-006	-4.132e-016	2.907e-006	2.907e-006
Total				2.089e-013	

Time for bias point: 0.28 sec.

Total time: 3.44 sec.

ATLAS> solve vcathode=-0.5

Obtaining static solution:

V( cathode ) = -0.5

```
proj      psi  n  p  psi  n  p
direct    x  x  x  rhs  rhs  rhs
i  j  m -5.00* -5.00* -5.00* -26.0* -17.3* -17.3*
```

```
-----
1  N -0.681 -0.681 -0.822 -26.8* -0.196 -1.681
2  N -2.265 -1.697 -1.927 -26.7* -3.167 -5.060
3  N -6.26* -5.27* -5.12* -26.7* -10.38 -12.09
```

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
cathode	-5.000e-001	2.160e-016	-6.865e-006	-6.865e-006	-6.865e-006
anode	0.000e+000	6.865e-006	-4.150e-016	6.865e-006	6.865e-006



Total -2.559e-011

Time for bias point: 0.64 sec.

Total time: 4.31 sec.

ATLAS> solve vcathode=-0.75

Obtaining static solution:

V( cathode ) = -0.75

proj	psi	n	p	psi	n	p
direct	x	x	x	rhs	rhs	rhs
i	j	m				
				-5.00*	-5.00*	-5.00*
				-26.0*	-17.3*	-17.3*

1	N	-0.707	-0.707	-1.061	-26.7*	-0.314	-1.960
2	N	-2.293	-1.757	-2.375	-26.8*	-3.511	-5.971
3	N	-6.29*	-5.24*	-5.52*	-26.8*	-10.10	-13.62

r

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
-----------	-------	----------	----------	----------	----------

cathode	-7.500e-001	4.246e-016	-1.457e-005	-1.457e-005	-1.457e-005
anode	0.000e+000	1.457e-005	-4.709e-016	1.457e-005	1.457e-005
Total				-1.873e-011	

Time for bias point: 0.36 sec.

Total time: 4.69 sec.

ATLAS> solve vcathode=-1

Obtaining static solution:

V( cathode ) = -1

proj	psi	n	p	psi	n	p
direct	x	x	x	rhs	rhs	rhs
i	j	m				
				-5.00*	-5.00*	-5.00*
				-26.0*	-17.3*	-17.3*

1	N	-0.733	-0.733	-1.283	-26.8*	-0.346	-2.459
2	N	-2.341	-1.822	-2.802	-26.9*	-3.358	-6.763
3	N	-6.39*	-5.33*	-6.20*	-26.9*	-11.03	-14.02

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
-----------	-------	----------	----------	----------	----------

```

cathode  -1.000e+000  9.638e-016 -2.845e-005 -2.845e-005 -2.845e-005
anode    0.000e+000  2.845e-005 -4.879e-016  2.845e-005  2.845e-005
Total                                         -9.653e-012

```

Time for bias point: 1.08 sec.  
Total time: 5.79 sec.

ATLAS> solve vcathode=-1.25

Obtaining static solution:

V( cathode ) = -1.25

```

proj      psi  n  p  psi  n  p
direct    x  x  x  rhs  rhs  rhs
i  j  m  -5.00* -5.00* -5.00* -26.0* -17.3* -17.3*
-----
1  N  -0.745 -0.745 -1.528 -26.6* -0.366 -3.145
2  N  -2.397 -1.837 -3.147 -26.7* -3.616 -6.993
3  N  -6.34* -5.48* -6.61* -26.6* -10.40 -14.18

```

```

Electrode  Va(V)  Jn(A/um)  Jp(A/um)  Jc(A/um)  Jt(A/um)
=====
cathode    -1.250e+000  2.827e-015 -5.197e-005 -5.197e-005 -5.197e-005
anode      0.000e+000  5.197e-005 -5.387e-016  5.197e-005  5.197e-005
Total                                           6.982e-012

```

Time for bias point: 0.19 sec.  
Total time: 6.00 sec.

ATLAS> solve vcathode=-1.5

Obtaining static solution:

V( cathode ) = -1.5

```

proj      psi  n  p  psi  n  p
direct    x  x  x  rhs  rhs  rhs
i  j  m  -5.00* -5.00* -5.00* -26.0* -17.3* -17.3*
-----
1  N  -0.775 -0.775 -1.892 -26.8* -0.515 -4.082
2  N  -2.462 -1.897 -3.292 -26.8* -3.583 -7.461
3  N  -6.32* -5.48* -7.10* -26.8* -11.03 -14.24

```

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
cathode	-1.500e+000	8.978e-015	-8.987e-005	-8.987e-005	-8.987e-005
anode	0.000e+000	8.987e-005	-6.244e-016	8.987e-005	8.987e-005
Total			8.533e-012		

Time for bias point: 0.64 sec.  
Total time: 6.86 sec.

ATLAS> log outfile=InGaP-td-IV-edit7.log  
ATLAS> solve vcathode=-2

Obtaining static solution:

V( cathode ) = -2

proj	psi	n	p	psi	n	p
direct	x	x	x	rhs	rhs	rhs
i j m	-5.00*	-5.00*	-5.00*	-26.0*	-17.3*	-17.3*
1	N	-0.359	-0.359	-1.207	-26.5*	0.340 -5.833
2	N	-1.762	-0.892	-2.510	-26.5*	-2.215 -6.531
3	N	-4.618	-3.849	-6.02*	-26.6*	-7.541 -12.32
4	N	-10.4*	-9.36*	-11.7*	-26.8*	-12.77 -14.51

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
cathode	-2.000e+000	1.711e-013	-2.358e-004	-2.358e-004	-2.358e-004
anode	0.000e+000	2.358e-004	-8.742e-016	2.358e-004	2.358e-004
Total			-2.242e-013		

Time for bias point: 0.42 sec.  
Total time: 7.34 sec.

ATLAS> solve vcathode=-1.90

Obtaining static solution:

V( cathode ) = -1.9

prev	psi	n	p	psi	n	p
direct	x	x	x	rhs	rhs	rhs
i j m	-5.00*	-5.00*	-5.00*	-26.0*	-17.3*	-17.3*

```

1   N  0.500 -0.241 -0.301 -13.51 -0.120 -0.310
2   N -0.341 -0.681  0.178 -26.6* -1.782 -1.964
3   N -3.526 -2.275 -1.357 -26.7* -6.242 -6.201
4   N -7.75* -7.22* -5.86* -26.5* -13.00 -14.36

```

```

Electrode   Va(V)   Jn(A/um)  Jp(A/um)  Jc(A/um)  Jt(A/um)
=====
cathode     -1.900e+000  9.486e-014 -1.968e-004 -1.968e-004 -1.968e-004
anode       0.000e+000  1.968e-004 -7.960e-016  1.968e-004  1.968e-004
Total                               9.797e-014

```

Time for bias point: 0.25 sec.  
Total time: 8.02 sec.

ATLAS> solve vcathode=-1.80

Obtaining static solution:

V( cathode ) = -1.8

```

proj      psi  n  p  psi  n  p
direct    x  x  x  rhs  rhs  rhs
i  j  m -5.00* -5.00* -5.00* -26.0* -17.3* -17.3*
-----
1   N -1.694 -1.694 -1.990 -26.6* -2.132 -6.912
2   N -4.209 -3.835 -4.873 -26.5* -7.096 -11.25
3   N -9.49* -9.00* -10.9* -26.6* -12.93 -14.19

```

```

Electrode   Va(V)   Jn(A/um)  Jp(A/um)  Jc(A/um)  Jt(A/um)
=====
cathode     -1.800e+000  5.130e-014 -1.633e-004 -1.633e-004 -1.633e-004
anode       0.000e+000  1.633e-004 -7.342e-016  1.633e-004  1.633e-004
Total                               -7.643e-014

```

Time for bias point: 0.20 sec.  
Total time: 8.49 sec.

ATLAS> solve vcathode=-1.70

Obtaining static solution:

V( cathode ) = -1.7

```

proj      psi  n  p  psi  n  p

```

```

direct   x   x   x   rhs  rhs  rhs
i  j  m -5.00* -5.00* -5.00* -26.0* -17.3* -17.3*

```

```

-----
1  N -1.663 -1.663 -2.182 -26.6* -2.063 -7.013
2  N -4.130 -3.782 -4.836 -26.7* -6.960 -11.01
3  N -9.39* -8.91* -10.8* -26.4* -12.83 -14.05

```

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
cathode	-1.700e+000	2.767e-014	-1.347e-004	-1.347e-004	-1.347e-004
anode	0.000e+000	1.347e-004	-6.887e-016	1.347e-004	1.347e-004
Total				-7.606e-014	

Time for bias point: 0.41 sec.  
Total time: 8.92 sec.

ATLAS> solve vcathode=-1.60

Obtaining static solution:

V( cathode ) = -1.6

```

proj     psi  n  p  psi  n  p
direct   x   x   x   rhs  rhs  rhs
i  j  m -5.00* -5.00* -5.00* -26.0* -17.3* -17.3*

```

```

-----
1  N -1.637 -1.637 -2.347 -26.8* -1.960 -7.372
2  N -4.058 -3.738 -4.797 -26.6* -6.823 -10.79
3  N -9.32* -8.81* -10.8* -26.8* -12.90 -14.06

```

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
cathode	-1.600e+000	1.535e-014	-1.104e-004	-1.104e-004	-1.104e-004
anode	0.000e+000	1.104e-004	-6.547e-016	1.104e-004	1.104e-004
Total				1.019e-013	

Time for bias point: 0.42 sec.  
Total time: 9.36 sec.

ATLAS> solve vcathode=-1.5

Obtaining static solution:

V( cathode ) = -1.5

```

proj      psi  n  p  psi  n  p
direct    x  x  x  rhs  rhs  rhs
i  j  m -5.00* -5.00* -5.00* -26.0* -17.3* -17.3*

```

```

-----
1  N -1.616 -1.616 -2.487 -26.7* -1.896 -7.839
2  N -3.997 -3.704 -4.763 -26.7* -6.649 -10.59
3  N -9.28* -8.72* -10.5* -26.7* -12.63 -14.24

```

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
cathode	-1.500e+000	8.978e-015	-8.987e-005	-8.987e-005	-8.987e-005
anode	0.000e+000	8.987e-005	-6.244e-016	8.987e-005	8.987e-005
Total				-1.597e-014	

Time for bias point: 0.20 sec.  
Total time: 10.05 sec.

ATLAS> solve vcathode=-1.40

Obtaining static solution:

V( cathode ) = -1.4

```

proj      psi  n  p  psi  n  p
direct    x  x  x  rhs  rhs  rhs
i  j  m -5.00* -5.00* -5.00* -26.0* -17.3* -17.3*

```

```

-----
1  N -1.599 -1.599 -2.223 -26.9* -1.878 -7.334
2  N -3.945 -3.681 -4.734 -26.8* -6.537 -10.41
3  N -9.26* -8.65* -10.2* -26.7* -12.90 -14.07

```

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
cathode	-1.400e+000	5.538e-015	-7.262e-005	-7.262e-005	-7.262e-005
anode	0.000e+000	7.262e-005	-5.916e-016	7.262e-005	7.262e-005
Total				-1.012e-013	

Time for bias point: 0.42 sec.  
Total time: 10.50 sec.

ATLAS> solve vcathode=-1.30

Obtaining static solution:

V( cathode ) = -1.3

```

proj      psi  n  p  psi  n  p
direct    x  x  x  rhs  rhs  rhs
i  j  m -5.00* -5.00* -5.00* -26.0* -17.3* -17.3*

```

```

-----
1  N -1.588 -1.588 -2.008 -26.7* -1.914 -6.285
2  N -3.901 -3.662 -4.710 -26.7* -6.496 -10.25
3  N -9.25* -8.59* -10.0* -26.8* -12.60 -14.04

```

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
cathode	-1.300e+000	3.528e-015	-5.822e-005	-5.822e-005	-5.822e-005
anode	0.000e+000	5.822e-005	-5.560e-016	5.822e-005	5.822e-005
Total			1.364e-014		

Time for bias point: 0.44 sec.  
Total time: 10.96 sec.

ATLAS> solve vcathode=-1.20

Obtaining static solution:

V( cathode ) = -1.2

```

proj      psi  n  p  psi  n  p
direct    x  x  x  rhs  rhs  rhs
i  j  m -5.00* -5.00* -5.00* -26.0* -17.3* -17.3*

```

```

-----
1  N -1.572 -1.572 -1.885 -26.7* -1.972 -5.682
2  N -3.866 -3.631 -4.689 -26.9* -6.522 -10.09
3  N -9.26* -8.56* -9.89* -26.8* -12.67 -13.96

```

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
cathode	-1.200e+000	2.267e-015	-4.628e-005	-4.628e-005	-4.628e-005
anode	0.000e+000	4.628e-005	-5.230e-016	4.628e-005	4.628e-005
Total			1.788e-013		

Time for bias point: 0.19 sec.  
Total time: 11.59 sec.

ATLAS> solve vcathode=-1.10

Obtaining static solution:

V( cathode ) = -1.1

```
proj      psi  n  p  psi  n  p
direct    x  x  x  rhs  rhs  rhs
i  j  m -5.00* -5.00* -5.00* -26.0* -17.3* -17.3*
```

```
-----
1  N -1.557 -1.557 -1.847 -26.8* -1.847 -5.219
2  N -3.838 -3.604 -4.667 -26.7* -6.535 -9.943
3  N -9.27* -8.57* -9.75* -26.9* -12.72 -14.09
```

```
Electrode  Va(V)  Jn(A/um)  Jp(A/um)  Jc(A/um)  Jt(A/um)
=====
cathode    -1.100e+000  1.463e-015 -3.646e-005 -3.646e-005 -3.646e-005
anode      0.000e+000  3.646e-005 -4.995e-016  3.646e-005  3.646e-005
Total                                     1.360e-013
```

Time for bias point: 0.41 sec.  
Total time: 12.02 sec.

ATLAS> solve vcathode=-1

Obtaining static solution:

V( cathode ) = -1

```
proj      psi  n  p  psi  n  p
direct    x  x  x  rhs  rhs  rhs
i  j  m -5.00* -5.00* -5.00* -26.0* -17.3* -17.3*
```

```
-----
1  N -1.544 -1.544 -1.864 -26.7* -1.763 -4.831
2  N -3.811 -3.581 -4.628 -26.8* -6.390 -9.807
3  N -9.28* -8.56* -9.55* -26.6* -12.60 -13.75
```

```
Electrode  Va(V)  Jn(A/um)  Jp(A/um)  Jc(A/um)  Jt(A/um)
=====
cathode    -1.000e+000  9.638e-016 -2.845e-005 -2.845e-005 -2.845e-005
anode      0.000e+000  2.845e-005 -4.879e-016  2.845e-005  2.845e-005
Total                                     -6.964e-015
```

Time for bias point: 0.43 sec.  
Total time: 12.47 sec.

ATLAS> solve vcathode=-0.90

Obtaining static solution:



V( cathode ) = -0.9

```
proj      psi  n  p  psi  n  p
direct    x  x  x  rhs  rhs  rhs
  i  j  m -5.00* -5.00* -5.00* -26.0* -17.3* -17.3*
-----
  1  N -1.533 -1.533 -1.940 -26.7* -1.722 -4.496
  2  N -3.784 -3.563 -4.377 -26.8* -6.268 -9.693
  3  N -9.31* -8.49* -9.14* -26.8* -12.77 -13.84
```

```
Electrode  Va(V)  Jn(A/um)  Jp(A/um)  Jc(A/um)  Jt(A/um)
=====
cathode    -9.000e-001  6.665e-016 -2.196e-005 -2.196e-005 -2.196e-005
anode      0.000e+000  2.196e-005 -4.836e-016  2.196e-005  2.196e-005
Total                                           4.268e-014
```

Time for bias point: 0.21 sec.  
Total time: 13.16 sec.

ATLAS> solve vcathode=-0.80

Obtaining static solution:

V( cathode ) = -0.8

```
proj      psi  n  p  psi  n  p
direct    x  x  x  rhs  rhs  rhs
  i  j  m -5.00* -5.00* -5.00* -26.0* -17.3* -17.3*
-----
  1  N -1.525 -1.525 -2.221 -26.8* -1.731 -4.202
  2  N -3.759 -3.551 -4.405 -26.9* -6.226 -9.635
  3  N -9.26* -8.42* -9.04* -26.9* -12.86 -13.70
```

```
Electrode  Va(V)  Jn(A/um)  Jp(A/um)  Jc(A/um)  Jt(A/um)
=====
cathode    -8.000e-001  4.883e-016 -1.675e-005 -1.675e-005 -1.675e-005
anode      0.000e+000  1.675e-005 -4.773e-016  1.675e-005  1.675e-005
Total                                           1.954e-013
```

Time for bias point: 0.17 sec.  
Total time: 13.66 sec.

ATLAS> solve vcathode=-0.70

Obtaining static solution:

$$V(\text{cathode}) = -0.7$$

```
proj      psi  n  p  psi  n  p
direct    x  x  x  rhs  rhs  rhs
  i  j  m -5.00* -5.00* -5.00* -26.0* -17.3* -17.3*
-----
  1  N -1.520 -1.520 -2.124 -26.8* -1.804 -3.944
  2  N -3.735 -3.550 -4.402 -26.7* -6.252 -9.763
  3  N -9.16* -8.37* -8.93* -26.8* -13.02 -13.64
```

```
Electrode  Va(V)  Jn(A/um)  Jp(A/um)  Jc(A/um)  Jt(A/um)
=====
cathode    -7.000e-001  3.711e-016 -1.262e-005 -1.262e-005 -1.262e-005
anode      0.000e+000  1.262e-005 -4.619e-016  1.262e-005  1.262e-005
Total                                           -1.877e-013
```

Time for bias point: 0.34 sec.

Total time: 14.03 sec.

ATLAS> solve vcathode=-0.60

Obtaining static solution:

$$V(\text{cathode}) = -0.6$$

```
proj      psi  n  p  psi  n  p
direct    x  x  x  rhs  rhs  rhs
  i  j  m -5.00* -5.00* -5.00* -26.0* -17.3* -17.3*
-----
  1  N -1.520 -1.520 -2.041 -26.7* -1.812 -3.720
  2  N -3.715 -3.552 -4.319 -26.8* -6.353 -9.582
  3  N -9.10* -8.35* -8.81* -26.8* -12.60 -13.46
```

```
Electrode  Va(V)  Jn(A/um)  Jp(A/um)  Jc(A/um)  Jt(A/um)
=====
cathode    -6.000e-001  2.839e-016 -9.380e-006 -9.380e-006 -9.380e-006
anode      0.000e+000  9.380e-006 -4.381e-016  9.380e-006  9.380e-006
Total                                           1.473e-014
```

Time for bias point: 0.62 sec.

Total time: 14.67 sec.

ATLAS> solve vcathode=-0.5

Obtaining static solution:

V( cathode ) = -0.5

proj	psi	n	p	psi	n	p
direct	x	x	x	rhs	rhs	rhs
i	j	m				
				-5.00*	-5.00*	-5.00*
				-26.0*	-17.3*	-17.3*

1	N	-1.508	-1.508	-1.970	-26.8*	-1.689	-3.529
2	N	-3.699	-3.526	-4.178	-26.7*	-6.260	-9.000
3	N	-9.07*	-8.36*	-8.69*	-26.9*	-12.77	-13.54

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
cathode	-5.000e-001	2.160e-016	-6.865e-006	-6.865e-006	-6.865e-006
anode	0.000e+000	6.865e-006	-4.150e-016	6.865e-006	6.865e-006
Total				1.671e-013	

Time for bias point: 0.36 sec.

Total time: 15.05 sec.

ATLAS> solve vcathode=-0.40

Obtaining static solution:

V( cathode ) = -0.4

proj	psi	n	p	psi	n	p
direct	x	x	x	rhs	rhs	rhs
i	j	m				
				-5.00*	-5.00*	-5.00*
				-26.0*	-17.3*	-17.3*

1	N	-1.496	-1.496	-1.866	-26.8*	-1.611	-3.374
2	N	-3.689	-3.498	-4.019	-26.8*	-6.087	-8.550
3	N	-9.06*	-8.43*	-8.56*	-26.8*	-12.67	-13.47

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
cathode	-4.000e-001	1.666e-016	-4.940e-006	-4.940e-006	-4.940e-006
anode	0.000e+000	4.940e-006	-4.034e-016	4.940e-006	4.940e-006
Total				3.897e-015	

Time for bias point: 1.05 sec.  
 Total time: 16.12 sec.

ATLAS> solve vcathode=-0.3

Obtaining static solution:

V( cathode ) = -0.3

proj	psi	n	p	psi	n	p
direct	x	x	x	rhs	rhs	rhs
i	j	m				
1	N	-1.483	-1.483	-1.759	-26.9*	-1.580 -3.263
2	N	-3.670	-3.471	-3.853	-26.8*	-6.012 -8.232
3	N	-8.99*	-8.18*	-8.44*	-27.0*	-12.67 -13.34

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
cathode	-3.000e-001	1.345e-016	-3.488e-006	-3.488e-006	-3.488e-006
anode	0.000e+000	3.488e-006	-4.074e-016	3.488e-006	3.488e-006
Total			-1.314e-013		

Time for bias point: 0.18 sec.  
 Total time: 16.32 sec.

ATLAS> solve vcathode=-0.2

Obtaining static solution:

V( cathode ) = -0.2

proj	psi	n	p	psi	n	p
direct	x	x	x	rhs	rhs	rhs
i	j	m				
1	N	-1.472	-1.472	-1.662	-27.0*	-1.607 -3.217
2	N	-3.648	-3.448	-3.692	-26.9*	-6.010 -8.036
3	N	-8.92*	-8.11*	-8.09*	-27.0*	-12.67 -13.24

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
cathode	-2.000e-001	1.145e-016	-2.410e-006	-2.410e-006	-2.410e-006
anode	0.000e+000	2.410e-006	-4.191e-016	2.410e-006	2.410e-006

Total -2.019e-013

Time for bias point: 0.57 sec.

Total time: 17.11 sec.

ATLAS> solve vcathode=-0.1

Obtaining static solution:

V( cathode ) = -0.1

```

proj      psi  n  p  psi  n  p
direct    x  x  x  rhs  rhs  rhs
  i  j  m -5.00* -5.00* -5.00* -26.0* -17.3* -17.3*
-----
  1  N -1.463 -1.463 -1.577 -26.8* -1.690 -3.292
  2  N -3.624 -3.434 -3.553 -26.9* -6.080 -8.076
  3  N -8.88* -8.02* -7.95* -26.8* -12.72 -13.20

```

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
cathode	-1.000e-001	9.932e-017	-1.626e-006	-1.626e-006	-1.626e-006
anode	0.000e+000	1.626e-006	-4.236e-016	1.626e-006	1.626e-006
Total				-3.191e-013	

Time for bias point: 0.18 sec.

Total time: 17.32 sec.

ATLAS> solve vcathode=0

Obtaining static solution:

V( cathode ) = 0

```

proj      psi  n  p  psi  n  p
direct    x  x  x  rhs  rhs  rhs
  i  j  m -5.00* -5.00* -5.00* -26.0* -17.3* -17.3*
-----
  1  N -1.459 -1.459 -1.509 -26.8* -1.630 -2.995
  2  N -3.600 -3.435 -3.448 -26.8* -6.119 -7.636
  3  N -8.63* -7.90* -7.82* -27.0* -12.72 -13.27

```

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
-----------	-------	----------	----------	----------	----------

```

cathode    0.000e+000  8.464e-017 -1.066e-006 -1.066e-006 -1.066e-006
anode      0.000e+000  1.066e-006 -4.104e-016  1.066e-006  1.066e-006
Total                                           -4.249e-014

```

Time for bias point: 0.62 sec.  
Total time: 18.20 sec.

ATLAS> solve vcathode=0.1

Obtaining static solution:

V( cathode ) = 0.1

```

proj      psi  n  p  psi  n  p
direct    x  x  x  rhs  rhs  rhs
  i  j  m -5.00* -5.00* -5.00* -26.0* -17.3* -17.3*
-----
  1  N -1.460 -1.460 -1.461 -26.9* -1.492 -2.759
  2  N -3.578 -3.443 -3.388 -26.8* -5.912 -7.208
  3  N -8.33* -7.78* -7.70* -27.0* -12.63 -13.13

```

```

Electrode  Va(V)  Jn(A/um)  Jp(A/um)  Jc(A/um)  Jt(A/um)
=====
cathode    1.000e-001  7.086e-017 -6.775e-007 -6.775e-007 -6.775e-007
anode      0.000e+000  6.775e-007 -3.840e-016  6.775e-007  6.775e-007
Total                                           1.432e-013

```

Time for bias point: 0.18 sec.  
Total time: 18.40 sec.

ATLAS> solve vcathode=0.2

Obtaining static solution:

V( cathode ) = 0.2

```

proj      psi  n  p  psi  n  p
direct    x  x  x  rhs  rhs  rhs
  i  j  m -5.00* -5.00* -5.00* -26.0* -17.3* -17.3*
-----
  1  N -1.430 -1.441 -1.430 -27.0* -1.406 -2.598
  2  N -3.559 -3.375 -3.326 -27.1* -5.750 -6.938
  3  N -8.14* -7.66* -7.57* -26.8* -12.63 -13.15

```

r

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
cathode	2.000e-001	6.070e-017	-4.148e-007	-4.148e-007	-4.148e-007
anode	0.000e+000	4.148e-007	-3.627e-016	4.148e-007	4.148e-007
Total				-6.693e-014	

Time for bias point: 0.61 sec.  
Total time: 19.19 sec.

ATLAS> solve vcathode=0.3

Obtaining static solution:

V( cathode ) = 0.3

proj	psi	n	p	psi	n	p			
direct	x	x	x	rhs	rhs	rhs			
i	j	m							
				-5.00*	-5.00*	-5.00*	-26.0*	-17.3*	-17.3*
1	N			-1.371	-1.412	-1.371	-27.0*	-1.381	-2.514
2	N			-3.467	-3.304	-3.210	-26.9*	-5.680	-6.769
3	N			-8.06*	-7.51*	-7.28*	-27.0*	-12.83	-13.23

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
cathode	3.000e-001	5.483e-017	-2.432e-007	-2.432e-007	-2.432e-007
anode	0.000e+000	2.432e-007	-3.645e-016	2.432e-007	2.432e-007
Total				1.751e-013	

Time for bias point: 0.18 sec.  
Total time: 19.40 sec.

ATLAS> solve vcathode=0.4

Obtaining static solution:

V( cathode ) = 0.4

proj	psi	n	p	psi	n	p			
direct	x	x	x	rhs	rhs	rhs			
i	j	m							
				-5.00*	-5.00*	-5.00*	-26.0*	-17.3*	-17.3*
1	N			-1.317	-1.383	-1.317	-26.9*	-1.443	-2.530
2	N			-3.382	-3.241	-3.106	-27.0*	-5.693	-6.718

3 N -8.05\* -7.22\* -7.11\* -27.0\* -12.80 -13.50

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
cathode	4.000e-001	5.045e-017	-1.355e-007	-1.355e-007	-1.355e-007
anode	0.000e+000	1.355e-007	-3.884e-016	1.355e-007	1.355e-007
Total				-1.890e-013	

Time for bias point: 0.62 sec.  
Total time: 20.25 sec.

ATLAS> solve vcathode=0.5

Obtaining static solution:

V( cathode ) = 0.5

proj	psi	n	p	psi	n	p
direct	x	x	x	rhs	rhs	rhs
i	j	m				
				-5.00*	-5.00*	-5.00*
				-26.0*	-17.3*	-17.3*
1	N			-1.274	-1.360	-1.274
				-26.9*	-1.430	-2.482
2	N			-3.270	-3.201	-3.030
				-27.1*	-5.810	-6.812
3	N			-7.94*	-7.09*	-6.98*
				-27.0*	-12.72	-13.22

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
cathode	5.000e-001	4.487e-017	-7.097e-008	-7.097e-008	-7.097e-008
anode	0.000e+000	7.097e-008	-4.082e-016	7.097e-008	7.097e-008
Total				8.148e-014	

Time for bias point: 0.38 sec.  
Total time: 20.65 sec.

ATLAS> solve vcathode=0.6

Obtaining static solution:

V( cathode ) = 0.6

proj	psi	n	p	psi	n	p
direct	x	x	x	rhs	rhs	rhs
i	j	m				
				-5.00*	-5.00*	-5.00*
				-26.0*	-17.3*	-17.3*



```

1   N -1.246 -1.345 -1.246 -27.0* -1.269 -2.362
2   N -3.170 -3.191 -3.000 -27.0* -5.496 -6.387
3   N -7.75* -6.97* -6.86* -27.1* -12.77 -13.24

```

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
cathode	6.000e-001	4.180e-017	-3.453e-008	-3.453e-008	-3.453e-008
anode	0.000e+000	3.453e-008	-3.920e-016	3.453e-008	3.453e-008
Total				-2.928e-014	

Time for bias point: 0.19 sec.

Total time: 21.30 sec.

ATLAS> solve vcathode=0.7

Obtaining static solution:

V( cathode ) = 0.7

```

proj      psi  n  p  psi  n  p
direct    x  x  x  rhs  rhs  rhs
i  j  m -5.00* -5.00* -5.00* -26.0* -17.3* -17.3*

```

```

-----
1   N -1.237 -1.343 -1.237 -27.1* -1.131 -2.200
2   N -3.096 -3.190 -2.997 -27.1* -5.272 -6.094
3   N -7.64* -6.84* -6.75* -27.2* -12.83 -13.26

```

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
cathode	7.000e-001	1.698e-016	-1.534e-008	-1.534e-008	-1.534e-008
anode	0.000e+000	1.534e-008	-3.376e-016	1.534e-008	1.534e-008
Total				-1.680e-013	

Time for bias point: 0.39 sec.

Total time: 21.72 sec.

ATLAS> solve vcathode=0.8

Obtaining static solution:

V( cathode ) = 0.8

```

proj      psi  n  p  psi  n  p
direct    x  x  x  rhs  rhs  rhs

```

```
i j m -5.00* -5.00* -5.00* -26.0* -17.3* -17.3*
```

```
-----
1 N -1.188 -1.305 -1.188 -27.1* -1.075 -2.150
2 N -3.048 -3.064 -2.871 -27.1* -5.149 -5.993
3 N -7.73* -6.71* -6.49* -27.0* -12.74 -13.03
```

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
cathode	8.000e-001	5.894e-015	-6.080e-009	-6.080e-009	-6.080e-009
anode	0.000e+000	6.080e-009	-4.573e-016	6.080e-009	6.080e-009
Total				8.908e-015	

Time for bias point: 0.18 sec.  
 Total time: 21.93 sec.

ATLAS> solve vcathode=0.9

Obtaining static solution:

V( cathode ) = 0.9

```
proj      psi  n  p  psi  n  p
direct    x  x  x  rhs  rhs  rhs
i j m -5.00* -5.00* -5.00* -26.0* -17.3* -17.3*
-----
1 N -1.137 -1.249 -1.137 -27.0* -1.143 -2.182
2 N -2.971 -2.946 -2.762 -27.2* -5.146 -6.063
3 N -7.66* -6.44* -6.34* -27.2* -12.60 -13.27
```

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
cathode	9.000e-001	2.552e-013	-2.082e-009	-2.081e-009	-2.081e-009
anode	0.000e+000	2.081e-009	-9.018e-015	2.081e-009	2.081e-009
Total				-1.986e-013	

Time for bias point: 0.69 sec.  
 Total time: 22.85 sec.

ATLAS> quit

## 2. Si Tunnel Junction Diode

The output file for this diode is over a smaller voltage range than those used in the thesis. This gives the results for the most critical voltages and keeps the size down to a reasonable amount.

ATLAS> #Simple Si tunnel diode

```

ATLAS> #Created by Robert J. Gelinas
ATLAS> mesh space.mult=1
ATLAS> x.mesh loc=-2 spac=0.2
ATLAS> x.mesh loc=2 spac=0.2
ATLAS> y.mesh loc=-0.2 spac=0.01
ATLAS> y.mesh loc=0 spac=0.005
ATLAS> y.mesh loc=0.2 spac=0.01
ATLAS> # Anode
ATLAS> region num=1 material=Si x.min=-2 x.max=2 y.min=-0.2 y.max=0
ATLAS> # Cathode
ATLAS> region num=2 material=Si x.min=-2 x.max=2 y.min=0 y.max=0.2
ATLAS> # Electrodes
ATLAS> electrode name=anode top

```

```

Electrode # 1
Name: anode
Number of boundary nodes: 21
Dimensions in microns:
    min    max
x -2.000e+000  2.000e+000
y -2.000e-001 -2.000e-001

```

```

ATLAS> electrode name=cathode bottom

```

```

Electrode # 2
Name: cathode
Number of boundary nodes: 21
Dimensions in microns:
    min    max
x -2.000e+000  2.000e+000
y  2.000e-001  2.000e-001

```

```

ATLAS> interface tunnel thermionic x.min=-2 x.max=2 y.min=-0.2 y.max=0.2

```

```

Mesh
Type:          non-cylindrical
Total grid points: 1197
Total triangles: 2240
Obtuse triangles: 0 (0 %)

```

```

Added      21 virtual hetero-interface nodes.
New total number of grid points =      1218 .

```

```

ATLAS> # Anode is p-type

```

```

ATLAS> doping region=1 p.type conc=1e20 uniform
ATLAS> # Cathode is n-type
ATLAS> doping region=2 n.type conc=1e20 uniform
ATLAS> struct outfile=situnneldiode.str

```

MASTER format file written to situnneldiode.str at Fri Dec 09 11:13:59 2005

```

ATLAS> tonyplot situnneldiode.str
ATLAS> models bbt.kl trap.tunnel
ATLAS> solve init

```

Starting: SPICES module.

Obtaining static solution:

```

init      psi  psi
direct    x   rhs
  i  j  m -5.00* -26.0*
-----
  1  1  G -1.518 -13.68
  2  1  G -1.314 -14.05
  3  1  G -0.980 -14.32
  4  1  G -0.931 -14.47
  5  1  G -0.877 -14.59
  6  1  G -0.816 -14.77
  7  1  G -0.743 -15.07
  8  1  G -2.703 -17.03
  9  1  G -13.6* -27.9*

```

```

ATLAS> log outfile=situnneldiode-iv.log
ATLAS> solve vanode=-1 vfinal=2 vstep=0.1 name=anode

```

Obtaining static solution:

V( anode ) = -1

```

prev      psi  n   p   psi  n   p
direct    x   x   x   rhs  rhs  rhs
  i  j  m -5.00* -5.00* -5.00* -26.0* -17.3* -17.3*
-----
  1  N  1.588 -0.811 -0.811 -23.23 -1.735 -2.036
  2  N -1.883  0.415  0.550 -29.1* -5.288 -5.589
  3  N -5.44* -4.937 -4.637 -29.1* -12.39 -12.67

```

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
anode	-1.000e+000	3.302e-010	-3.036e-006	-3.035e-006	-3.035e-006
cathode	0.000e+000	3.036e-006	-3.302e-010	3.035e-006	3.035e-006
Total			1.287e-014		

Time for bias point: 1.24 sec.  
Total time: 4.67 sec.

Obtaining static solution:

$$V(\text{ anode }) = -0.9$$

prev	psi	n	p	psi	n	p
direct	x	x	x	rhs	rhs	rhs
i j m	-5.00*	-5.00*	-5.00*	-26.0*	-17.3*	-17.3*
-----						
1	N	0.588	-0.289	-0.289	-28.0*	-3.641 -3.942
2	N	-3.791	-0.690	-0.690	-29.4*	-9.134 -9.433
3	N	-9.28*	-7.95*	-7.65*	-29.3*	-14.97 -13.77

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
anode	-9.000e-001	2.061e-010	-1.776e-006	-1.776e-006	-1.776e-006
cathode	0.000e+000	1.776e-006	-2.061e-010	1.776e-006	1.776e-006
Total			-1.343e-014		

Time for bias point: 0.74 sec.  
Total time: 5.42 sec.

Obtaining static solution:

$$V(\text{ anode }) = -0.8$$

proj	psi	n	p	psi	n	p
direct	x	x	x	rhs	rhs	rhs
i j m	-5.00*	-5.00*	-5.00*	-26.0*	-17.3*	-17.3*
-----						
1	N	-3.501	-1.377	-1.327	-29.4*	-7.158 -7.459
2	N	-7.31*	-7.88*	-7.81*	-29.4*	-14.97 -13.78

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
-----------	-------	----------	----------	----------	----------

```

=====
anode      -8.000e-001  1.228e-010 -9.898e-007 -9.897e-007 -9.897e-007
cathode    0.000e+000  9.898e-007 -1.228e-010  9.897e-007  9.897e-007
Total                                     3.153e-014

```

Time for bias point: 0.58 sec.  
Total time: 6.00 sec.

Obtaining static solution:

V( anode ) = -0.7

```

proj      psi  n  p  psi  n  p
direct    x  x  x  rhs  rhs  rhs
i  j  m -5.00* -5.00* -5.00* -26.0* -17.3* -17.3*

```

```

-----
1  N -3.516 -1.591 -1.457 -29.4* -7.184 -7.485
2  N -7.34* -8.14* -8.00* -29.4* -15.07 -13.76

```

```

Electrode  Va(V)  Jn(A/um)  Jp(A/um)  Jc(A/um)  Jt(A/um)

```

```

=====
anode      -7.000e-001  6.939e-011 -5.218e-007 -5.217e-007 -5.217e-007
cathode    0.000e+000  5.218e-007 -6.939e-011  5.217e-007  5.217e-007
Total                                     1.902e-015

```

Time for bias point: 0.77 sec.  
Total time: 6.77 sec.

Obtaining static solution:

V( anode ) = -0.6

```

proj      psi  n  p  psi  n  p
direct    x  x  x  rhs  rhs  rhs
i  j  m -5.00* -5.00* -5.00* -26.0* -17.3* -17.3*

```

```

-----
1  N -3.531 -1.830 -1.696 -29.4* -7.209 -7.510
2  N -7.37* -8.42* -8.28* -29.3* -14.89 -13.75

```

```

Electrode  Va(V)  Jn(A/um)  Jp(A/um)  Jc(A/um)  Jt(A/um)

```

```

=====
anode      -6.000e-001  3.684e-011 -2.578e-007 -2.578e-007 -2.578e-007

```

cathode 0.000e+000 2.578e-007 -3.684e-011 2.578e-007 2.578e-007  
 Total -8.797e-015

Time for bias point: 0.67 sec.  
 Total time: 7.48 sec.

Obtaining static solution:

V( anode ) = -0.5

proj	psi	n	p	psi	n	p
direct	x	x	x	rhs	rhs	rhs
i	j	m				
				-5.00*	-5.00*	-5.00*
				-26.0*	-17.3*	-17.3*
-----						
1	N			-3.546	-2.098	-1.963
2	N			-29.4*	-7.234	-7.535
				-7.40*	-8.73*	-8.59*
				-29.3*	-15.06	-14.13

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
anode	-5.000e-001	1.818e-011	-1.181e-007	-1.181e-007	-1.181e-007
cathode	0.000e+000	1.181e-007	-1.181e-011	1.181e-007	1.181e-007
Total			-2.470e-014		

Time for bias point: 0.50 sec.  
 Total time: 7.98 sec.

Obtaining static solution:

V( anode ) = -0.4

proj	psi	n	p	psi	n	p
direct	x	x	x	rhs	rhs	rhs
i	j	m				
				-5.00*	-5.00*	-5.00*
				-26.0*	-17.3*	-17.3*
-----						
1	N			-3.561	-2.399	-2.265
2	N			-29.4*	-7.259	-7.560
				-7.43*	-9.08*	-8.93*
				-29.4*	-14.97	-14.00

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
anode	-4.000e-001	8.228e-012	-4.943e-008	-4.942e-008	-4.942e-008
cathode	0.000e+000	4.943e-008	-8.228e-012	4.942e-008	4.942e-008
Total			1.401e-014		

Time for bias point: 0.69 sec.  
 Total time: 8.79 sec.

Obtaining static solution:

V( anode ) = -0.3

proj	psi	n	p	psi	n	p
direct	x	x	x	rhs	rhs	rhs
i	j	m				
				-5.00*	-5.00*	-5.00*
				-26.0*	-17.3*	-17.3*
-----						
1	N	-3.575	-2.743	-2.608	-29.4*	-7.284 -7.585
2	N	-7.46*	-9.23*	-9.23*	-29.4*	-14.97 -14.05

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
anode	-3.000e-001	3.357e-012	-1.858e-008	-1.858e-008	-1.858e-008
cathode	0.000e+000	1.858e-008	-3.357e-012	1.858e-008	1.858e-008
Total					-2.540e-014

Time for bias point: 0.49 sec.  
 Total time: 9.29 sec.

Obtaining static solution:

V( anode ) = -0.2

proj	psi	n	p	psi	n	p
direct	x	x	x	rhs	rhs	rhs
i	j	m				
				-5.00*	-5.00*	-5.00*
				-26.0*	-17.3*	-17.3*
-----						
1	N	-3.589	-3.139	-3.004	-29.4*	-7.308 -7.609
2	N	-7.49*	-9.27*	-9.27*	-29.4*	-15.02 -14.07

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
anode	-2.000e-001	1.207e-012	-6.131e-009	-6.130e-009	-6.130e-009
cathode	0.000e+000	6.131e-009	-1.207e-012	6.130e-009	6.130e-009
Total					1.016e-015

Time for bias point: 0.72 sec.



Total time: 10.02 sec.

Obtaining static solution:

V( anode ) = -0.1

proj		psi	n	p	psi	n	p	
direct		x	x	x	rhs	rhs	rhs	
i	j	m	-5.00*	-5.00*	-5.00*	-26.0*	-17.3*	-17.3*

-----  
1 N -3.602 -3.602 -3.517 -29.4\* -7.331 -7.632  
2 N -7.51\* -9.30\* -9.30\* -29.6\* -15.07 -14.05

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
anode	-1.000e-001	3.718e-013	-1.724e-009	-1.723e-009	-1.723e-009
cathode	0.000e+000	1.724e-009	-3.718e-013	1.723e-009	1.723e-009
Total				3.529e-015	

Time for bias point: 0.84 sec.

Total time: 10.87 sec.

Obtaining static solution:

V( anode ) = 1.49012e-008

proj		psi	n	p	psi	n	p	
direct		x	x	x	rhs	rhs	rhs	
i	j	m	-5.00*	-5.00*	-5.00*	-26.0*	-17.3*	-17.3*

-----  
1 N -3.616 -3.608 -3.606 -29.4\* -7.355 -7.656  
2 N -7.54\* -8.66\* -8.57\* -29.4\* -14.97 -14.00

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
anode	1.490e-008	9.434e-014	-3.968e-010	-3.968e-010	-3.968e-010
cathode	0.000e+000	3.968e-010	-9.434e-014	3.968e-010	3.968e-010
Total				5.783e-021	

Time for bias point: 0.48 sec.

Total time: 11.35 sec.

Obtaining static solution:

$$V(\text{ anode }) = 0.1$$

```
proj      psi  n  p  psi  n  p
direct    x  x  x  rhs  rhs  rhs
  i  j  m -5.00* -5.00* -5.00* -26.0* -17.3* -17.3*
```

```
-----
  1  N -3.629 -2.663 -2.660 -29.4* -7.378 -7.679
  2  N -7.57* -8.75* -8.47* -29.4* -15.07 -14.05
```

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
-----------	-------	----------	----------	----------	----------

```
=====
anode      1.000e-001 1.869e-014 -7.086e-011 -7.084e-011 -7.084e-011
cathode    0.000e+000 7.085e-011 -1.869e-014 7.083e-011 7.083e-011
Total                                           -1.192e-014
```

Time for bias point: 0.70 sec.

Total time: 12.05 sec.

Obtaining static solution:

$$V(\text{ anode }) = 0.2$$

```
proj      psi  n  p  psi  n  p
direct    x  x  x  rhs  rhs  rhs
  i  j  m -5.00* -5.00* -5.00* -26.0* -17.3* -17.3*
```

```
-----
  1  N -3.642 -2.106 -2.043 -29.3* -7.400 -7.701
  2  N -7.59* -9.28* -8.98* -29.4* -14.97 -14.15
```

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
-----------	-------	----------	----------	----------	----------

```
=====
anode      2.000e-001 2.724e-015 -9.104e-012 -9.101e-012 -9.101e-012
cathode    0.000e+000 9.086e-012 -2.704e-015 9.084e-012 9.084e-012
Total                                           -1.704e-014
```

Time for bias point: 1.04 sec.

Total time: 13.09 sec.

Obtaining static solution:

V( anode ) = 0.3

proj		psi	n	p	psi	n	p
direct		x	x	x	rhs	rhs	rhs
i	j	m					
1	N	-3.655	-2.563	-2.432	-29.4*	-7.423	-7.724
2	N	-7.62*	-9.43*	-9.43*	-29.4*	-15.07	-14.05

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
anode	3.000e-001	2.200e-015	-7.400e-013	-7.378e-013	-7.378e-013
cathode	0.000e+000	7.469e-013	-1.225e-015	7.457e-013	7.457e-013
Total			7.872e-015		

Time for bias point: 0.71 sec.

Total time: 13.80 sec.

Obtaining static solution:

V( anode ) = 0.4

proj		psi	n	p	psi	n	p
direct		x	x	x	rhs	rhs	rhs
i	j	m					
1	N	-3.667	-3.439	-3.304	-29.6*	-7.445	-7.746
2	N	-7.64*	-9.47*	-9.47*	-29.4*	-14.97	-14.45

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
anode	4.000e-001	9.327e-014	1.502e-014	1.083e-013	1.083e-013
cathode	0.000e+000	-6.202e-014	-4.664e-014	-1.087e-013	-1.087e-013
Total			-3.698e-016		

Time for bias point: 0.50 sec.

Total time: 14.30 sec.

Obtaining static solution:

V( anode ) = 0.5

```

proj      psi  n  p  psi  n  p
direct    x  x  x  rhs  rhs  rhs
i  j  m -5.00* -5.00* -5.00* -26.0* -17.3* -17.3*

```

```

-----
1  N -3.680 -3.680 -3.680 -29.4* -7.466 -7.767
2  N -7.67* -9.50* -9.32* -29.3* -15.02 -14.34

```

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
anode	5.000e-001	4.461e-012	2.221e-012	6.682e-012	6.682e-012
cathode	0.000e+000	-4.457e-012	-2.230e-012	-6.688e-012	-6.688e-012
Total				-5.446e-015	

Time for bias point: 0.68 sec.  
Total time: 15.11 sec.

Obtaining static solution:

V( anode ) = 0.6

```

proj      psi  n  p  psi  n  p
direct    x  x  x  rhs  rhs  rhs
i  j  m -5.00* -5.00* -5.00* -26.0* -17.3* -17.3*

```

```

-----
1  N -3.692 -3.692 -3.692 -29.3* -7.488 -7.789
2  N -7.69* -9.53* -9.53* -29.4* -14.97 -14.41

```

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
anode	6.000e-001	2.134e-010	1.067e-010	3.200e-010	3.200e-010
cathode	0.000e+000	-2.134e-010	-1.067e-010	-3.200e-010	-3.200e-010
Total				1.223e-015	

Time for bias point: 0.59 sec.  
Total time: 16.02 sec.

Obtaining static solution:

V( anode ) = 0.7

```

proj      psi  n  p  psi  n  p
direct    x  x  x  rhs  rhs  rhs
i  j  m -5.00* -5.00* -5.00* -26.0* -17.3* -17.3*

```

```

-----
1  N -3.704 -3.704 -3.704 -29.4* -7.508 -7.809
2  N -7.72* -9.09* -9.05* -29.7* -15.07 -14.34

```

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
anode	7.000e-001	1.020e-008	5.102e-009	1.530e-008	1.530e-008
cathode	0.000e+000	-1.020e-008	-5.102e-009	-1.530e-008	-1.530e-008
Total			7.820e-015		

Time for bias point: 0.72 sec.  
Total time: 16.75 sec.

Obtaining static solution:

$$V(\text{ anode }) = 0.8$$

```

proj      psi  n  p  psi  n  p
direct    x  x  x  rhs  rhs  rhs
i  j  m -5.00* -5.00* -5.00* -26.0* -17.3* -17.3*

```

```

-----
1  N -3.719 -3.226 -3.311 -29.4* -7.530 -7.831
2  N -7.74* -7.36* -7.38* -29.4* -15.02 -14.70

```

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
anode	8.000e-001	4.876e-007	2.438e-007	7.315e-007	7.315e-007
cathode	0.000e+000	-4.876e-007	-2.438e-007	-7.315e-007	-7.315e-007
Total			1.524e-015		

Time for bias point: 0.47 sec.  
Total time: 17.55 sec.

Obtaining static solution:

$$V(\text{ anode }) = 0.9$$

```

proj      psi  n  p  psi  n  p
direct    x  x  x  rhs  rhs  rhs

```

i j m -5.00\* -5.00\* -5.00\* -26.0\* -17.3\* -17.3\*

-----  
 1 N -3.874 -2.536 -2.660 -29.4\* -7.694 -7.993  
 2 N -7.89\* -6.35\* -6.42\* -29.4\* -14.92 -14.66

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
anode	9.000e-001	2.324e-005	1.163e-005	3.487e-005	3.487e-005
cathode	0.000e+000	-2.324e-005	-1.163e-005	-3.487e-005	-3.487e-005
Total			-1.742e-015		

Time for bias point: 0.67 sec.  
 Total time: 18.34 sec.

Obtaining static solution:

V( anode ) = 1

proj psi n p psi n p  
 direct x x x rhs rhs rhs  
 i j m -5.00\* -5.00\* -5.00\* -26.0\* -17.3\* -17.3\*

-----  
 1 N -2.621 -1.687 -1.803 -29.2\* -6.322 -6.459  
 2 N -5.83\* -4.175 -4.634 -29.6\* -12.14 -13.08

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
anode	1.000e+000	1.086e-003	5.466e-004	1.633e-003	1.633e-003
cathode	0.000e+000	-1.086e-003	-5.466e-004	-1.633e-003	-1.633e-003
Total			2.212e-017		

Time for bias point: 0.54 sec.  
 Total time: 18.89 sec.

Obtaining static solution:

V( anode ) = 1.1

proj psi n p psi n p  
 direct x x x rhs rhs rhs  
 i j m -5.00\* -5.00\* -5.00\* -26.0\* -17.3\* -17.3\*

-----

```

1   N -1.038 -0.645 -0.689 -27.5* -2.493 -2.877
2   N -3.154 -1.656 -1.720 -29.3* -5.894 -6.136
3   N -6.02* -5.22* -5.08* -29.6* -12.51 -12.36

```

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
anode	1.100e+000	4.195e-002	2.176e-002	6.372e-002	6.372e-002
cathode	0.000e+000	-4.195e-002	-2.176e-002	-6.372e-002	-6.372e-002
Total			2.956e-015		

Time for bias point: 0.92 sec.

Total time: 19.81 sec.

Obtaining static solution:

V( anode ) = 1.2

```

proj      psi  n  p  psi  n  p
direct    x  x  x  rhs  rhs  rhs
i  j  m -5.00* -5.00* -5.00* -26.0* -17.3* -17.3*
-----
1   N -0.346 -0.039 -0.042 -25.95 -0.102 -0.378
2   N -0.484 0.316 0.295 -26.8* -0.977 -1.326
3   N -1.286 -1.259 -1.277 -27.9* -2.808 -3.062
4   N -3.057 -3.014 -3.015 -29.5* -6.417 -6.689

```

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
anode	1.200e+000	5.399e-001	2.929e-001	8.328e-001	8.328e-001
cathode	0.000e+000	-5.399e-001	-2.929e-001	-8.328e-001	-8.328e-001
Total			-2.707e-010		

Time for bias point: 1.07 sec.

Total time: 21.00 sec.

Obtaining static solution:

V( anode ) = 1.3

```

proj      psi  n  p  psi  n  p
direct    x  x  x  rhs  rhs  rhs
i  j  m -5.00* -5.00* -5.00* -26.0* -17.3* -17.3*

```

```

-----
1   N -0.426 -0.087 -0.085 -24.99 0.030 -0.202
2   N -0.445 -0.279 -0.275 -26.3* -0.707 -1.106
3   N -1.315 -1.688 -1.685 -27.4* -2.693 -3.083
4   N -3.239 -3.631 -3.617 -29.2* -6.648 -7.040

```

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
anode	1.300e+000	2.077e+000	1.148e+000	3.225e+000	3.225e+000
cathode	0.000e+000	-2.077e+000	-1.148e+000	-3.225e+000	-3.225e+000
Total					-1.337e-009

Time for bias point: 1.08 sec.  
Total time: 22.24 sec.

Obtaining static solution:

$$V(\text{ anode }) = 1.4$$

```

proj      psi  n  p  psi  n  p
direct    x  x  x  rhs  rhs  rhs
i  j  m -5.00* -5.00* -5.00* -26.0* -17.3* -17.3*

```

```

-----
1   N -0.711 -0.350 -0.344 -25.77 -0.708 -1.026
2   N -1.321 -1.437 -1.371 -27.0* -2.649 -3.042
3   N -3.331 -3.624 -3.670 -28.9* -6.858 -7.103

```

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
anode	1.400e+000	4.755e+000	2.656e+000	7.411e+000	7.411e+000
cathode	0.000e+000	-4.755e+000	-2.656e+000	-7.411e+000	-7.411e+000
Total					-9.137e-009

Time for bias point: 0.99 sec.  
Total time: 23.24 sec.

Obtaining static solution:

$$V(\text{ anode }) = 1.5$$

```

proj      psi  n  p  psi  n  p
direct    x  x  x  rhs  rhs  rhs

```



i j m -5.00\* -5.00\* -5.00\* -26.0\* -17.3\* -17.3\*

```
-----
1  N -0.873 -0.625 -0.628 -25.63 -1.148 -1.640
2  N -1.850 -2.151 -2.108 -28.1* -4.068 -4.332
3  N -4.746 -5.01* -5.09* -28.8* -9.624 -9.760
```

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
anode	1.500e+000	8.520e+000	4.808e+000	1.333e+001	1.333e+001
cathode	0.000e+000	-8.520e+000	-4.808e+000	-1.333e+001	-1.333e+001
Total			5.492e-011		

Time for bias point: 0.89 sec.  
Total time: 24.20 sec.

Obtaining static solution:

V( anode ) = 1.6

```
proj      psi  n  p  psi  n  p
direct    x  x  x  rhs  rhs  rhs
i j m -5.00* -5.00* -5.00* -26.0* -17.3* -17.3*
-----
1  N -0.903 -0.851 -0.861 -25.74 -1.397 -1.938
2  N -2.138 -2.662 -2.670 -28.0* -4.944 -5.027
3  N -5.62* -5.90* -6.14* -28.8* -11.22 -11.24
```

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
anode	1.600e+000	1.325e+001	7.551e+000	2.080e+001	2.080e+001
cathode	0.000e+000	-1.325e+001	-7.551e+000	-2.080e+001	-2.080e+001
Total			3.403e-012		

Time for bias point: 0.79 sec.  
Total time: 25.00 sec.

Obtaining static solution:

V( anode ) = 1.7

```
proj      psi  n  p  psi  n  p
direct    x  x  x  rhs  rhs  rhs
```

i j m -5.00\* -5.00\* -5.00\* -26.0\* -17.3\* -17.3\*

```
-----
1 N -0.917 -1.037 -1.051 -25.96 -1.563 -2.107
2 N -2.337 -3.033 -3.114 -28.4* -5.525 -5.482
3 N -6.29* -6.53* -6.81* -28.5* -12.33 -12.23
```

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
anode	1.700e+000	1.876e+001	1.079e+001	2.955e+001	2.955e+001
cathode	0.000e+000	-1.876e+001	-1.079e+001	-2.955e+001	-2.955e+001
Total			2.949e-013		

Time for bias point: 0.71 sec.  
Total time: 25.72 sec.

Obtaining static solution:

$$V(\text{ anode }) = 1.8$$

```
proj      psi  n  p  psi  n  p
direct    x  x  x  rhs  rhs  rhs
i j m -5.00* -5.00* -5.00* -26.0* -17.3* -17.3*
-----
1 N -0.946 -1.199 -1.213 -25.80 -1.706 -2.232
2 N -2.507 -3.315 -3.470 -28.3* -5.931 -5.860
3 N -6.82* -7.02* -7.28* -28.4* -13.25 -13.01
```

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
anode	1.800e+000	2.485e+001	1.442e+001	3.927e+001	3.927e+001
cathode	0.000e+000	-2.485e+001	-1.442e+001	-3.927e+001	-3.927e+001
Total			4.263e-014		

Time for bias point: 0.90 sec.  
Total time: 26.72 sec.

Obtaining static solution:

$$V(\text{ anode }) = 1.9$$

```
proj      psi  n  p  psi  n  p
direct    x  x  x  rhs  rhs  rhs
```

```
i j m -5.00* -5.00* -5.00* -26.0* -17.3* -17.3*
```

```
-----  
1 N -0.995 -1.351 -1.360 -26.0* -1.851 -2.354  
2 N -2.670 -3.544 -3.761 -28.2* -6.258 -6.220
```

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
anode	1.900e+000	3.133e+001	1.833e+001	4.966e+001	4.966e+001
cathode	0.000e+000	-3.133e+001	-1.833e+001	-4.966e+001	-4.966e+001
Total			8.296e-007		

Time for bias point: 0.52 sec.  
Total time: 27.24 sec.

Obtaining static solution:

V( anode ) = 2

```
proj      psi  n  p  psi  n  p  
direct    x  x  x  rhs  rhs  rhs  
i j m -5.00* -5.00* -5.00* -26.0* -17.3* -17.3*
```

```
-----  
1 N -1.060 -1.495 -1.499 -25.99 -2.005 -2.485  
2 N -2.834 -3.697 -4.011 -28.1* -6.573 -6.581
```

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
anode	2.000e+000	3.805e+001	2.241e+001	6.047e+001	6.047e+001
cathode	0.000e+000	-3.805e+001	-2.241e+001	-6.047e+001	-6.047e+001
Total			3.246e-007		

Time for bias point: 0.70 sec.  
Total time: 28.06 sec.

```
ATLAS> tonyplot situnneldiode-iv.log  
ATLAS> quit
```

### 3. Ge tunnel diode

This output file is over a smaller voltage range than those used in the thesis for the same reasons as stated for the Si tunnel diode.

```
ATLAS> #Ge Tunnel Diode  
ATLAS> #Created by Robert J. Gelinas  
ATLAS> mesh space.mult=1
```

```

ATLAS> x.mesh loc=-2 spac=0.1
ATLAS> x.mesh loc=2 spac=0.1
ATLAS> y.mesh loc=-0.2 spac=0.01
ATLAS> y.mesh loc=0 spac=0.001
ATLAS> y.mesh loc=0.2 spac=0.01
ATLAS> # Anode
ATLAS> region num=1 material=Ge x.min=-2 x.max=2 y.min=-0.2 y.max=0
ATLAS> # Cathode
ATLAS> region num=2 material=Ge x.min=-2 x.max=2 y.min=0 y.max=0.2
ATLAS> # Electrodes
ATLAS> electrode name=anode top

```

Electrode # 1

```

Name: anode
Number of boundary nodes: 41
Dimensions in microns:
    min    max
x -2.000e+000 2.000e+000
y -2.000e-001 -2.000e-001

```

```

ATLAS> electrode name=cathode bottom

```

Electrode # 2

```

Name: cathode
Number of boundary nodes: 41
Dimensions in microns:
    min    max
x -2.000e+000 2.000e+000
y 2.000e-001 2.000e-001

```

```

ATLAS> interface tunnel thermionic x.min=-2 x.max=2 y.min=-0.2 y.max=0.2

```

Mesh

```

Type:          non-cylindrical
Total grid points: 4223
Total triangles: 8160
Obtuse triangles: 0 (0 %)

```

```

Added      41 virtual hetero-interface nodes.
New total number of grid points =      4264 .

```

```

ATLAS> # Anode is p-type
ATLAS> doping region=1 p.type conc=2e24 uniform
ATLAS> # Cathode is n-type

```

```

ATLAS> doping region=2 n.type conc=4e21 uniform
ATLAS> struct outfile=getunnelldiode.str

```

MASTER format file written to getunnelldiode.str at Fri Dec 09 11:23:17 2005

```

ATLAS> tonyplot getunnelldiode.str
ATLAS> models bbt.kl trap.tunnel
ATLAS> solve init

```

Starting: BLAZE module.

Obtaining static solution:

```

init      psi  psi
direct    x   rhs
  i  j  m -5.00* -26.0*
-----
  1  1  G -1.883 -10.80
  2  1  G -2.333 -11.47
  3  1  G -3.335 -12.55
  4  1  G -5.39* -14.61

```

```

ATLAS> log outfile=getunnelldiode-iv.log
ATLAS> solve vanode=-1 vfinal=2 vstep=0.1 name=anode

```

Obtaining static solution:

V( anode ) = -1

```

prev      psi  n   p   psi  n   p
direct    x   x   x   rhs  rhs  rhs
  i  j  m -5.00* -5.00* -5.00* -26.0* -17.3* -17.3*
-----
  1  N  1.588 0.835 1.147 -23.03 1.374 -1.346
  2  N -1.280 -0.016 -0.700 -25.71 -1.271 -6.494
  3  N -3.931 -3.982 -3.079 -25.71 -6.561 -8.403

```

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
anode	-1.000e+000	1.975e-006	-2.239e-001	-2.239e-001	-2.239e-001
cathode	0.000e+000	2.239e-001	-3.611e-006	2.239e-001	2.239e-001
Total					-3.761e-010

Time for bias point: 4.73 sec.  
 Total time: 8.67 sec.

Obtaining static solution:

V( anode ) = -0.9

prev		psi	n	p	psi	n	p
direct		x	x	x	rhs	rhs	rhs
i	j	m					
			-5.00*	-5.00*	-5.00*	-26.0*	-17.3* -17.3*
-----							
1	N	0.588	-0.954	-0.954	-23.91	-0.433	-3.344
2	N	-3.096	-1.524	-2.529	-25.69	-4.924	-8.478
3	N	-7.59*	-7.53*	-6.24*	-25.69	-12.05	-8.477

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
anode	-9.000e-001	1.761e-006	-1.903e-001	-1.903e-001	-1.903e-001
cathode	0.000e+000	1.903e-001	-3.351e-006	1.903e-001	1.903e-001
Total			1.013e-011		

Time for bias point: 4.80 sec.  
 Total time: 13.52 sec.

Obtaining static solution:

V( anode ) = -0.8

proj		psi	n	p	psi	n	p
direct		x	x	x	rhs	rhs	rhs
i	j	m					
			-5.00*	-5.00*	-5.00*	-26.0*	-17.3* -17.3*
-----							
1	N	-2.817	-2.094	-2.019	-25.61	-3.279	-8.459
2	N	-5.96*	-6.70*	-4.917	-25.61	-10.64	-8.528

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
anode	-8.000e-001	1.558e-006	-1.601e-001	-1.601e-001	-1.601e-001
cathode	0.000e+000	1.601e-001	-3.079e-006	1.601e-001	1.601e-001
Total			-1.579e-009		

Time for bias point: 3.52 sec.  
 Total time: 17.04 sec.

Obtaining static solution:

V( anode ) = -0.7

proj	psi	n	p	psi	n	p
direct	x	x	x	rhs	rhs	rhs
i	j	m	-5.00*	-5.00*	-5.00*	-26.0* -17.3* -17.3*
-----						
1	N	-2.849	-2.038	-1.976	-25.65	-3.335 -8.478
2	N	-6.02*	-6.66*	-4.894	-25.65	-10.79 -8.439

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
anode	-7.000e-001	1.365e-006	-1.330e-001	-1.330e-001	-1.330e-001
cathode	0.000e+000	1.330e-001	-2.799e-006	1.330e-001	1.330e-001
Total			1.198e-009		

Time for bias point: 3.17 sec.  
 Total time: 20.23 sec.

Obtaining static solution:

V( anode ) = -0.6

proj	psi	n	p	psi	n	p
direct	x	x	x	rhs	rhs	rhs
i	j	m	-5.00*	-5.00*	-5.00*	-26.0* -17.3* -17.3*
-----						
1	N	-2.880	-1.979	-1.928	-25.69	-3.389 -8.819
2	N	-6.08*	-6.62*	-4.866	-25.69	-10.93 -8.877

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
anode	-6.000e-001	1.183e-006	-1.091e-001	-1.091e-001	-1.091e-001
cathode	0.000e+000	1.091e-001	-2.515e-006	1.091e-001	1.091e-001
Total			-3.376e-012		

Time for bias point: 3.47 sec.  
 Total time: 23.70 sec.

Obtaining static solution:

$$V(\text{ anode }) = -0.5$$

```
proj      psi  n  p  psi  n  p
direct    x  x  x  rhs  rhs  rhs
i  j  m -5.00* -5.00* -5.00* -26.0* -17.3* -17.3*
```

```
-----
1  N -2.910 -1.917 -1.875 -25.69 -3.441 -8.849
2  N -6.14* -6.57* -4.834 -25.70 -11.06 -8.785
```

```
Electrode  Va(V)  Jn(A/um)  Jp(A/um)  Jc(A/um)  Jt(A/um)
=====
anode      -5.000e-001  1.014e-006 -8.805e-002 -8.805e-002 -8.805e-002
cathode    0.000e+000  8.806e-002 -2.230e-006  8.805e-002  8.805e-002
Total                                -4.500e-010
```

Time for bias point: 3.51 sec.

Total time: 27.21 sec.

Obtaining static solution:

$$V(\text{ anode }) = -0.4$$

```
proj      psi  n  p  psi  n  p
direct    x  x  x  rhs  rhs  rhs
i  j  m -5.00* -5.00* -5.00* -26.0* -17.3* -17.3*
```

```
-----
1  N -2.939 -1.850 -1.817 -25.74 -3.492 -8.801
2  N -6.20* -6.51* -4.796 -25.74 -11.19 -8.804
```

```
Electrode  Va(V)  Jn(A/um)  Jp(A/um)  Jc(A/um)  Jt(A/um)
=====
anode      -4.000e-001  8.559e-007 -6.982e-002 -6.982e-002 -6.982e-002
cathode    0.000e+000  6.983e-002 -1.947e-006  6.982e-002  6.982e-002
Total                                7.226e-010
```

Time for bias point: 3.36 sec.

Total time: 30.58 sec.



Obtaining static solution:

$$V(\text{ anode }) = -0.3$$

proj	psi	n	p	psi	n	p
direct	x	x	x	rhs	rhs	rhs
i	j	m				
				-5.00*	-5.00*	-5.00*
				-26.0*	-17.3*	-17.3*
-----						
1	N			-2.967	-1.779	-1.752
2	N			-6.26*	-6.45*	-4.753
				-25.73	-3.541	-8.721
				-25.74	-11.30	-8.801

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
anode	-3.000e-001	7.108e-007	-5.422e-002	-5.422e-002	-5.422e-002
cathode	0.000e+000	5.422e-002	-1.670e-006	5.422e-002	5.422e-002
Total			-1.825e-010		

Time for bias point: 3.24 sec.

Total time: 33.84 sec.

Obtaining static solution:

$$V(\text{ anode }) = -0.2$$

proj	psi	n	p	psi	n	p
direct	x	x	x	rhs	rhs	rhs
i	j	m				
				-5.00*	-5.00*	-5.00*
				-26.0*	-17.3*	-17.3*
-----						
1	N			-2.995	-1.703	-1.682
2	N			-6.31*	-6.37*	-4.704
				-25.64	-3.588	-8.796
				-25.64	-11.40	-8.824

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
anode	-2.000e-001	5.785e-007	-4.107e-002	-4.106e-002	-4.106e-002
cathode	0.000e+000	4.107e-002	-1.402e-006	4.106e-002	4.106e-002
Total			-1.790e-010		

r  
Time for bias point: 3.28 sec.

Total time: 37.13 sec.

Obtaining static solution:

V( anode ) = -0.1

```
proj      psi  n  p  psi  n  p
direct    x  x  x  rhs  rhs  rhs
i  j  m -5.00* -5.00* -5.00* -26.0* -17.3* -17.3*
```

```
-----
1  N -3.021 -1.621 -1.604 -25.79 -3.634 -8.767
2  N -6.37* -6.29* -4.647 -25.78 -11.50 -8.818
```

```
r
Electrode  Va(V)  Jn(A/um)  Jp(A/um)  Jc(A/um)  Jt(A/um)
```

```
=====
anode      -1.000e-001  4.596e-007  -3.019e-002  -3.019e-002  -3.019e-002
cathode     0.000e+000  3.019e-002  -1.148e-006  3.019e-002  3.019e-002
Total                                           9.607e-010
```

```
r
Time for bias point:  3.35 sec.
Total time:          40.50 sec.
```

Obtaining static solution:

V( anode ) = 1.49012e-008

```
proj      psi  n  p  psi  n  p
direct    x  x  x  rhs  rhs  rhs
i  j  m -5.00* -5.00* -5.00* -26.0* -17.3* -17.3*
```

```
-----
1  N -3.047 -1.532 -1.519 -25.69 -3.679 -8.855
2  N -6.42* -6.19* -4.583 -25.68 -11.64 -8.772
```

```
Electrode  Va(V)  Jn(A/um)  Jp(A/um)  Jc(A/um)  Jt(A/um)
```

```
=====
anode      1.490e-008  3.544e-007  -2.140e-002  -2.140e-002  -2.140e-002
cathode     0.000e+000  2.140e-002  -9.119e-007  2.140e-002  2.140e-002
Total                                           6.376e-010
```

```
r
Time for bias point:  3.47 sec.
Total time:          43.96 sec.
```

Obtaining static solution:

V( anode ) = 0.1

```

proj      psi  n  p  psi  n  p
direct    x  x  x  rhs  rhs  rhs
i  j  m -5.00* -5.00* -5.00* -26.0* -17.3* -17.3*

```

```

-----
1  N -3.072 -1.435 -1.426 -25.78 -3.722 -8.766
2  N -6.47* -6.08* -4.510 -25.78 -11.69 -8.770

```

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
anode	1.000e-001	2.633e-007	-1.450e-002	-1.450e-002	-1.450e-002
cathode	0.000e+000	1.450e-002	-6.970e-007	1.450e-002	1.450e-002
Total				-5.514e-010	

Time for bias point: 3.15 sec.

Total time: 47.12 sec.

Obtaining static solution:

V( anode ) = 0.2

```

proj      psi  n  p  psi  n  p
direct    x  x  x  rhs  rhs  rhs
i  j  m -5.00* -5.00* -5.00* -26.0* -17.3* -17.3*

```

```

-----
1  N -3.097 -1.420 -1.322 -25.66 -3.765 -9.115
2  N -6.52* -6.06* -4.425 -25.66 -11.76 -9.110

```

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
anode	2.000e-001	1.864e-007	-9.280e-003	-9.279e-003	-9.279e-003
cathode	0.000e+000	9.280e-003	-5.074e-007	9.279e-003	9.279e-003
Total				5.589e-011	

Time for bias point: 3.17 sec.

Total time: 50.30 sec.

Obtaining static solution:

V( anode ) = 0.3

```

proj      psi  n  p  psi  n  p

```

```

direct      x   x   x   rhs  rhs  rhs
i   j   m -5.00* -5.00* -5.00* -26.0* -17.3* -17.3*

```

```

-----
1   N -3.122 -1.474 -1.215 -25.80 -3.806 -9.082
2   N -6.56* -6.10* -4.399 -25.80 -11.84 -9.087

```

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
anode	3.000e-001	1.239e-007	-5.510e-003	-5.510e-003	-5.510e-003
cathode	0.000e+000	5.510e-003	-3.466e-007	5.510e-003	5.510e-003
Total				-2.093e-010	

Time for bias point: 3.36 sec.  
Total time: 53.68 sec.

Obtaining static solution:

$$V(\text{ anode }) = 0.4$$

```

proj      psi  n   p   psi  n   p
direct    x   x   x   rhs  rhs  rhs
i   j   m -5.00* -5.00* -5.00* -26.0* -17.3* -17.3*

```

```

-----
1   N -3.145 -1.549 -1.396 -25.84 -3.846 -9.019
2   N -6.61* -6.14* -4.644 -25.83 -12.01 -9.011

```

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
anode	4.000e-001	7.554e-008	-2.958e-003	-2.958e-003	-2.958e-003
cathode	0.000e+000	2.959e-003	-2.230e-007	2.958e-003	2.958e-003
Total				-4.236e-010	

Time for bias point: 3.41 sec.  
Total time: 57.08 sec.

Obtaining static solution:

$$V(\text{ anode }) = 0.5$$

```

proj      psi  n   p   psi  n   p
direct    x   x   x   rhs  rhs  rhs
i   j   m -5.00* -5.00* -5.00* -26.0* -17.3* -17.3*

```

```

-----
1   N -3.169 -1.715 -0.103 -25.73 -3.885 -8.692
2   N -6.65* -6.27* -3.377 -25.73 -12.00 -9.115

```

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
anode	5.000e-001	4.142e-008	-1.378e-003	-1.378e-003	-1.378e-003
cathode	0.000e+000	1.379e-003	-4.162e-007	1.378e-003	1.378e-003
Total				4.786e-010	

Time for bias point: 3.54 sec.

Total time: 60.64 sec.

Obtaining static solution:

$$V(\text{ anode }) = 0.6$$

```

proj      psi  n  p  psi  n  p
direct    x  x  x  rhs  rhs  rhs
i  j  m -5.00* -5.00* -5.00* -26.0* -17.3* -17.3*

```

```

-----
1   N -3.192 -0.911 1.239 -25.72 -3.924 -7.030
2   N -6.70* -5.42* -3.241 -25.73 -12.01 -9.402

```

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
anode	6.000e-001	5.231e-008	-5.061e-004	-5.060e-004	-5.060e-004
cathode	0.000e+000	5.203e-004	-1.423e-005	5.060e-004	5.060e-004
Total				-9.249e-011	

Time for bias point: 3.15 sec.

Total time: 63.80 sec.

Obtaining static solution:

$$V(\text{ anode }) = 0.7$$

```

proj      psi  n  p  psi  n  p
direct    x  x  x  rhs  rhs  rhs
i  j  m -5.00* -5.00* -5.00* -26.0* -17.3* -17.3*

```

```

-----
1   N -3.223 0.814 -0.404 -25.76 -3.979 -5.909

```

2 N -6.76\* -4.468 -3.795 -25.73 -12.06 -9.421

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
anode	7.000e-001	1.637e-006	5.384e-004	5.400e-004	5.400e-004
cathode	0.000e+000	1.384e-004	-6.785e-004	-5.400e-004	-5.400e-004
Total			1.995e-010		

Time for bias point: 3.24 sec.

Total time: 67.05 sec.

Obtaining static solution:

V( anode ) = 0.8

proj	psi	n	p	psi	n	p	
direct	x	x	x	rhs	rhs	rhs	
i	j	m					
1	N	-3.314	-0.281	-2.420	-25.72	-4.147	-6.534
2	N	-6.93*	-6.33*	-5.78*	-25.69	-12.04	-9.684

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
anode	8.000e-001	7.807e-005	3.243e-002	3.251e-002	3.251e-002
cathode	0.000e+000	-5.748e-005	-3.245e-002	-3.251e-002	-3.251e-002
Total			2.129e-011		

Time for bias point: 3.48 sec.

Total time: 70.53 sec.

Obtaining static solution:

V( anode ) = 0.9

proj	psi	n	p	psi	n	p	
direct	x	x	x	rhs	rhs	rhs	
i	j	m					
1	N	-1.608	-1.608	-1.605	-25.61	-1.574	-1.630
2	N	-3.550	-4.763	-3.226	-25.62	-6.453	-5.420
3	N	-8.50*	-7.48*	-7.34*	-25.62	-11.95	-9.860

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
anode	9.000e-001	3.735e-003	1.534e+000	1.538e+000	1.538e+000
cathode	0.000e+000	-3.734e-003	-1.534e+000	-1.538e+000	-1.538e+000
Total			4.629e-012		

Time for bias point: 4.89 sec.  
Total time: 75.43 sec.

Obtaining static solution:

$$V(\text{ anode }) = 1$$

proj		psi	n	p	psi	n	p
direct		x	x	x	rhs	rhs	rhs
	i j m						
		-5.00*	-5.00*	-5.00*	-26.0*	-17.3*	-17.3*
1	N	-0.299	-0.300	-0.296	-24.11	0.715	2.376
2	N	-1.836	-1.060	-0.629	-24.80	-0.741	-0.234
3	N	-3.126	-3.487	-3.135	-25.63	-5.553	-3.914
4	N	-7.26*	-7.42*	-7.29*	-25.63	-11.74	-9.951

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
anode	1.000e+000	1.783e-001	5.424e+001	5.442e+001	5.442e+001
cathode	0.000e+000	-1.783e-001	-5.424e+001	-5.442e+001	-5.442e+001
Total			8.058e-012		

Time for bias point: 5.66 sec.  
Total time: 81.10 sec.

Obtaining static solution:

$$V(\text{ anode }) = 1.1$$

proj		psi	n	p	psi	n	p
direct		x	x	x	rhs	rhs	rhs
	i j m						
		-5.00*	-5.00*	-5.00*	-26.0*	-17.3*	-17.3*
1	N	-0.113	-0.131	-0.083	-21.33	1.895	3.725
2	N	-0.474	-0.239	-0.105	-22.85	1.601	1.651

3 N -1.287 -1.506 -1.775 -24.21 -0.206 0.244  
 4 N -3.435 -3.444 -3.620 -25.63 -3.906 -4.231

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
anode	1.100e+000	8.221e+000	7.313e+002	7.395e+002	7.395e+002
cathode	0.000e+000	-8.221e+000	-7.313e+002	-7.395e+002	-7.395e+002
Total			-1.393e-005		

Time for bias point: 5.71 sec.  
 Total time: 86.81 sec.

Obtaining static solution:

V( anode ) = 1.2

proj	psi	n	p	psi	n	p
direct	x	x	x	rhs	rhs	rhs
i	j	m				
				-5.00*	-5.00*	-5.00*
				-26.0*	-17.3*	-17.3*
-----						
1	N	-0.351	-0.379	-0.157	-20.80	2.915 3.570
2	N	-0.707	-0.601	-0.423	-21.87	1.633 1.341
3	N	-1.533	-2.023	-1.885	-22.94	-0.965 -1.163
4	N	-3.756	-3.992	-3.832	-25.47	-4.843 -4.859

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
anode	1.200e+000	2.855e+002	4.941e+003	5.227e+003	5.227e+003
cathode	0.000e+000	-2.855e+002	-4.941e+003	-5.227e+003	-5.227e+003
Total			-8.985e-005		

Time for bias point: 6.52 sec.  
 Total time: 93.34 sec.

Obtaining static solution:

V( anode ) = 1.3

proj	psi	n	p	psi	n	p
direct	x	x	x	rhs	rhs	rhs
i	j	m				
				-5.00*	-5.00*	-5.00*
				-26.0*	-17.3*	-17.3*
-----						
1	N	-0.476	-0.023	-0.266	-19.39	4.574 3.944



```

2   N -0.651 0.596 -0.920 -20.11 3.487 2.898
3   N -1.786 -1.322 -2.156 -21.79 1.173 0.381
4   N -4.192 -3.572 -4.409 -24.50 -3.512 -4.179

```

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
anode	1.300e+000	3.174e+003	1.648e+004	1.965e+004	1.965e+004
cathode	0.000e+000	-3.174e+003	-1.648e+004	-1.965e+004	-1.965e+004
Total			3.171e-006		

Time for bias point: 6.18 sec.

Total time: 99.53 sec.

Obtaining static solution:

$$V(\text{ anode }) = 1.4$$

```

proj      psi  n  p  psi  n  p
direct    x  x  x  rhs  rhs  rhs
i  j  m -5.00* -5.00* -5.00* -26.0* -17.3* -17.3*
-----
1   N -0.484 -0.106 -0.360 -19.08 4.785 3.861
2   N -0.430 -0.596 -0.974 -20.24 2.706 2.070
3   N -2.237 -2.444 -2.537 -21.99 -0.159 -0.905
4   N -5.17* -5.65* -5.75* -25.20 -6.229 -6.853

```

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
anode	1.400e+000	9.582e+003	2.972e+004	3.931e+004	3.931e+004
cathode	0.000e+000	-9.582e+003	-2.972e+004	-3.931e+004	-3.931e+004
Total			-2.267e-008		

Time for bias point: 6.14 sec.

Total time: 105.69 sec.

Obtaining static solution:

$$V(\text{ anode }) = 1.5$$

```

proj      psi  n  p  psi  n  p
direct    x  x  x  rhs  rhs  rhs
i  j  m -5.00* -5.00* -5.00* -26.0* -17.3* -17.3*

```

```

-----
1   N -0.324 -0.351 -0.682 -19.39 4.144 3.280
2   N -1.013 -1.470 -1.553 -20.80 2.188 1.690
3   N -2.988 -3.879 -3.877 -22.94 -2.082 -2.628

```

```

=====
Electrode   Va(V)   Jn(A/um)  Jp(A/um)  Jc(A/um)  Jt(A/um)
=====

```

```

=====
anode      1.500e+000 1.615e+004 4.027e+004 5.641e+004 5.641e+004
cathode    0.000e+000 -1.615e+004 -4.027e+004 -5.641e+004 -5.641e+004
Total                                           1.448e-006

```

Time for bias point: 5.03 sec.  
Total time: 110.73 sec.

Obtaining static solution:

V( anode ) = 1.6

```

proj      psi   n   p   psi   n   p
direct    x   x   x   rhs  rhs  rhs
i   j   m -5.00* -5.00* -5.00* -26.0* -17.3* -17.3*

```

```

-----
1   N -0.633 -0.771 -1.123 -19.79 3.239 2.417
2   N -1.938 -2.319 -2.513 -21.09 0.323 -0.175
3   N -4.864 -5.43* -5.75* -24.48 -5.650 -6.161

```

```

=====
Electrode   Va(V)   Jn(A/um)  Jp(A/um)  Jc(A/um)  Jt(A/um)
=====

```

```

=====
anode      1.600e+000 2.259e+004 4.948e+004 7.207e+004 7.207e+004
cathode    0.000e+000 -2.259e+004 -4.948e+004 -7.207e+004 -7.207e+004
Total                                           -8.164e-009

```

Time for bias point: 5.06 sec.  
Total time: 115.80 sec.

Obtaining static solution:

V( anode ) = 1.7

```

proj      psi   n   p   psi   n   p
direct    x   x   x   rhs  rhs  rhs

```

i j m -5.00\* -5.00\* -5.00\* -26.0\* -17.3\* -17.3\*

-----  
 1 N -0.978 -1.111 -1.469 -20.15 2.584 1.746  
 2 N -2.622 -3.036 -3.154 -22.31 -1.056 -1.594

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
anode	1.700e+000	2.915e+004	5.822e+004	8.737e+004	8.737e+004
cathode	0.000e+000	-2.915e+004	-5.822e+004	-8.737e+004	-8.737e+004
Total			3.801e-003		

Time for bias point: 3.33 sec.  
 Total time: 119.16 sec.

Obtaining static solution:

$$V(\text{ anode }) = 1.8$$

proj psi n p psi n p  
 direct x x x rhs rhs rhs  
 i j m -5.00\* -5.00\* -5.00\* -26.0\* -17.3\* -17.3\*

-----  
 1 N -1.171 -1.316 -1.655 -20.52 2.217 1.377  
 2 N -3.006 -3.449 -3.649 -22.31 -1.902 -2.462

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
anode	1.800e+000	3.579e+004	6.665e+004	1.024e+005	1.024e+005
cathode	0.000e+000	-3.579e+004	-6.665e+004	-1.024e+005	-1.024e+005
Total			5.598e-004		

Time for bias point: 3.61 sec.  
 Total time: 122.79 sec.

Obtaining static solution:

$$V(\text{ anode }) = 1.9$$

proj psi n p psi n p  
 direct x x x rhs rhs rhs  
 i j m -5.00\* -5.00\* -5.00\* -26.0\* -17.3\* -17.3\*

```

1   N -1.301 -1.471 -1.816 -20.59 1.949 1.171
2   N -3.277 -3.756 -4.068 -22.84 -2.565 -3.140

```

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
anode	1.900e+000	4.243e+004	7.482e+004	1.173e+005	1.173e+005
cathode	0.000e+000	-4.243e+004	-7.482e+004	-1.173e+005	-1.173e+005
Total			1.414e-004		

```

Time for bias point: 3.24 sec.
Total time:         126.03 sec.

```

Obtaining static solution:

V( anode ) = 2

```

proj      psi  n  p  psi  n  p
direct    x  x  x  rhs  rhs  rhs
i  j  m -5.00* -5.00* -5.00* -26.0* -17.3* -17.3*

```

```

-----
1   N -1.403 -1.606 -1.945 -20.36 1.718 0.986
2   N -3.517 -4.027 -4.384 -23.18 -3.171 -3.757

```

```
r
```

Electrode	Va(V)	Jn(A/um)	Jp(A/um)	Jc(A/um)	Jt(A/um)
anode	2.000e+000	4.906e+004	8.275e+004	1.318e+005	1.318e+005
cathode	0.000e+000	-4.906e+004	-8.275e+004	-1.318e+005	-1.318e+005
Total			4.434e-005		

```

Time for bias point: 3.22 sec.
Total time:         129.28 sec.

```

```

ATLAS> tonyplot getunnelldiode-iv.log
ATLAS> quit

```

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