4.2 Terminal Characteristics of Junction Diodes

Reading Assignment: pp. 173-179

Now that we understand ideal diodes, let’s consider the kind of diode that we can make—the *p-n junction diode*!

**HO: THE JUNCTION DIODE**

We can describe most of the junction diode curve with an exact mathematical expression!

**HO: THE JUNCTION DIODE EQUATION**

Let’s look closer at this junction diode equation—there are alternative ways to express it!

**HO: THE JUNCTION DIODE FORWARD BIAS EQUATION**

Now we can analyze some(!) circuits with junction diodes.

**EXAMPLE: A JUNCTION DIODE CIRCUIT**
Finally, let’s consider the rate at which diodes absorb energy!

**HO: DIODE POWER DISSIPATION**
The Junction Diode Curve

Junction diodes are real diodes!

We can build them and we can buy them and we can insert them in real working circuits!

In many ways, junction diodes are similar to ideal diodes.

But—in many other ways—junction diodes are profoundly different from their ideal counterpart.

First, we note that a junction diode has a very similar circuit symbol:

Thus, the junction diode is asymmetric!
Symbol and notation

The names of each terminal are identical to that of the ideal diode:

![Symbol of Junction Diode]

Likewise, the current-voltage notations are very similar (but not exact!) to the ideal diode:

![Current-Voltage Notations of Junction Diode]
Why they call it a junction diode

Q: You say that we can actually make these junction diodes? Of what are they made?

A: They are made from two types of semiconductor material (usually Silicon), called p-type and n-type.

The region where the p-type Silicon and the n-typed Silicon touch is known as the p-n junction.

It is this p-n junction that gives junction diodes their name—and it is the complex physical phenomena that occur at the junction that gives the junction diode its diode-like behavior!
First recall the ideal diode

Q: So what about its device equation—I suppose it is non-linear?

A: Absolutely!

Recall the behavior of the ideal diode could be plotted on the $i,v$ plane as:
Now for the junction diode

Now, compare and contrast this with the behavior of a junction diode:

Note that unlike ideal diodes, this junction diode curve is continuous!
**Trust me, you’ll miss these annoying things**

**Q:** Great!

So we **don’t** have those **annoying** piecewise linear equations, and we **don’t** have those **annoying** conditions (i.e., inequalities), and most of all we **don’t** have those **annoying bias modes**!?

**A:** Yes and no.

We actually will find that all those annoying things you mentioned can actually **help** when analyzing circuits with junction diodes.

Thus, we tend to describe a **junction** diode in **ideal** diode terms!
3 Regions

For example, when we look at the junction diode curve, we can see three amorphous “regions”, where the current/voltage relationships are distinctly different from each other.

Let’s look at each of these three regions.
Region 1

In this region of the junction diode curve, we find that “significant” positive current (i.e., from anode to cathode) is flowing.

Likewise, we find that the voltage across the diode is a “relatively” small—but positive—value!

We will find that this “small” positive voltage (provided the junction diode current is significant) will be somewhere in the vicinity of 600 to 900 mV, for most junction diodes.

Moreover, we will see that this voltage is “somewhat” constant; it changes “very little” as the diode current increases.

⇒ In other words, the curve in this region is “nearly” vertical!
Smells like forward bias

**Q:** Hey! Doesn’t this sound a little like a **forward biased ideal diode**?

**A:** Indeed it **does**!

The current is positive, and the voltage is a (approximately) constant value that is **close** to a zero value.

Essentially, this **region** of the junction diode curve describes an **approximate** (i.e., non-ideal) version of the **forward bias mode**.

Thus, we call **region 1** of the p-n junction diode curve:

"**The Forward Bias Region**"
From the standpoint of our mechanical analogy, it is if our flow valve requires a little more pressure at side A for it to “pop-open” and allow current to flow.

\[ P_A \text{ slightly larger than } P_C \]

\[ \therefore P_A - P_C > 0 \]

Similarly, we find that the junction diode requires a little more potential (i.e., voltage) at the anode in order for current to flow.
Region 2

In this region of the junction diode curve, we find that almost no current is flowing.

Q: You say “almost” no current is flowing; doesn’t this imply that there is some current flowing?

A: Very astute—that’s exactly what it implies!
There’s negative current!

The p-n junction diode curve in this region appears to lie precisely on the $v_D$-axis; it looks like part of the $i_D = 0$ "curve".

But, appearances are deceiving, and if we look more closely, we find that it actually lies a "tiny" bit below the $v_D$-axis.

Q: Below the $v_D$-axis!

That means the current is negative—it’s flowing from the cathode toward the anode?

A: Exactly correct!

But this shouldn’t be too big of a surprise, as the voltage in this region of the junction diode curve is negative (i.e., non-positive).
Smells like reverse bias

Thus, in this region, the junction diode voltage is (mostly) negative, and the junction diode current is “nearly” zero.

Essentially, this region of the junction diode curve describes an approximate (i.e., non-ideal) version of the reverse bias mode.

Thus, we call region 2 of the p-n junction diode curve:

“The Reverse Bias Region”
**Mechanical Analogy**

From the standpoint of our *mechanical analogy*, it is if our flow valve *leaks* (a tiny bit) when there is more pressure at the side C than side A—when the flow value is *shut*.

Similarly, if we find that the *junction diode* “leaks” a little current from anode to cathode, then its voltage is *negative*.
Region 3

In this region of the junction diode curve, we find that there is “significant” negative current flowing!

This negative current can be relatively “small”, or it can be large—but it must be negative!
We've not seen this before!

Q: What about the voltage?

A: In this region, the diode voltage is “very" negative (e.g., -30 to -60 Volts!).

Moreover, this negative voltage is “approximately" constant with respect to current—more negative current causes only a “tiny" change in the diode voltage.

Q: The voltage across the diode is “nearly" independent of the current through it—it sounds like a (negative) voltage source!

A: Very much like one.

But remember, the current must be negative.

Q: OK, I don’t see how this is anything like ideal diode behavior.

A: It’s not! This is the most non-ideal of the three junction diode regions—it has no analogy to ideal diode behavior what-so-ever!
Mechanical Analogy

From the standpoint of our mechanical analogy, it is as if we have placed too much reverse pressure across our flow valve.

Instead of leaking just a bit, the valve sort of "blows a gasket", and the valve pops open. As a result, current flows in "significant" quantities from side C to side A!
The Breakdown region

Similarly, for the junction diode, if we place “too much” negative voltage across the device, “significant” negative current will begin to flow.

As a result, we call region 3 of the p-n junction diode curve:

“The Breakdown Region Bias Region”

Q: So, if a junction diode enters breakdown, it is destroyed?

A: Nope! Not unless it melts.
It's not as bad as it sounds

Once we reduce the negative voltage, the junction diode will revert back to the "reverse bias region", or even the "forward bias region"—breakdown is not as bad as the name suggests!

Q: So, provide me with the precise mathematical boundaries, that unambiguously delineates when a junction diode is unequivocally in either:

1. Forward bias mode
2. Reverse bias mode
3. Breakdown mode

A: Whoa, whoa, whoa!!!!!!!

We can't do this—your thinking about this all wrong.

Remember, the junction diode curve is continuous; there are no well-defined boundaries between the "forward bias region" of this continuous curve, or the "reverse bias region" of this continuous curve, or the "breakdown region" of this continuous curve.
Ambiguity

There are “regions” of this continuous curve where specific characteristics can be ascribed (e.g., diode current is positive), but where one region ends and another starts is a bit ambiguous.
For example, let's say we measure the voltage across and current through three identical junction diodes that occupy three different locations in an operating DC circuit.

For the first junction diode we measure:

\[ V_{D1} = 0.67 \, V \quad \text{and} \quad I_{D1} = 231 \, mA \]

For the second we measure:

\[ V_{D2} = -12.7 \, V \quad \text{and} \quad I_{D2} = -12 \, \mu A \]

And for the third:

\[ V_{D3} = -52.0 \, V \quad \text{and} \quad I_{D3} = -69.1 \, mA \]
Clearly!
What regions mean

Hopefully it is clear to you that:

- the first junction diode measurement lies in the "forward bias region" of the continuous junction diode curve,

- the second measurement lies in the "reverse bias region" of the continuous junction diode curve,

- and the third measurement lies in the "breakdown region" of the continuous junction diode curve.
Here's the problem

Now consider two more measurements:

\[ v_{D4} = 0.31 \text{ V} \quad \text{and} \quad i_{D4} = 0.07 \text{ mA} \]

\[ v_{D5} = -51.7 \text{ V} \quad \text{and} \quad i_{D5} = -0.23 \text{ mA} \]

Neither of these two points lie unambiguously in any of the 3 "regions", rather they lie in the transition "knee" between two regions.
Those darn bunny ears

The fourth measurement is sort of between the forward and reverse bias “regions”, while the fifth is kind of between the breakdown and reverse bias regions.

We could argue, for example, that the forth measurement is simultaneously in the forward and reverse bias region, or we could argue that it lies in neither.

Basically, the problem is determining when “tiny” becomes “significant”, and vice versa.

Q: So what’s the point? You’ve been “bunny-earing” almost every phrase in the handout: “almost”, “tiny”, “significant”, “nearly”, “too much”—are we studying circuits or poetry?

A: We engineers often find approximations to be quite helpful in solving difficult problems, even if they do introduce “a little” error.
Get used to it

But, this ambiguity about what kind of error is “acceptable” can frustrate students—what if this error results in lost points on an exam?

You’ll have to learn to accept some ambiguity as we learn about junction diodes.

WE must make approximations in order to “easily” analyze junction diode circuits, and these approximations will use the definable characteristics of these three regions of the junction diode curve!
The Junction Diode Equation

Q: OK, you have explained the relationship between junction diode current and junction diode voltage using this elegant plot:
Here's the math

But, I'm an engineer; I need to determine numbers—values like $i_D = 234\ mA$ and $v_D = 0.68\ V$.

→ I need the mathematical relationship between $i_D$ and $v_D$!

A: You sure do! The relationship between the current through a junction diode ($i_D$) and the voltage across it ($v_D$) is:

$$
i_D = I_s \left( e^{v_D/V_T} - 1 \right) \quad \text{for} \quad v_D > -V_{ZK}$$

Q: Good golly! Just what do those dog-gone parameters $n$, $I_s$, $V_{ZK}$ and $V_T$ mean?

A: Similar to the resistance value $R$ of a resistor, or the capacitance $C$ of a capacitor, there are three parameters that specify the performance of a junction diode.
Device parameters

Specifically, the three parameters are:

1. $I_s \equiv \text{Saturation (or scale) Current}$. This value depends on diode material, size, and most of all—temperature. This value typically doubles for every 10 degree C increase in temperature!

   Typical values range from $10^{-8}$ to $10^{-15}$ Amps (i.e., tiny)!

2. $n \equiv$ a constant called the ideality factor (i.e. a “fudge factor”).

   Typically, this ideality factor is between one and two (i.e., $1 \leq n \leq 2$), but is usually close to one (e.g., $n = 1.2$).

   If the ideality factor is not specified, then we use the nominal value of $n = 1.0$. 
3. $V_{zk} = $ Zener Breakdown Voltage. When the junction diode is operating in the **breakdown** region, the diode voltage is approximately $V_D = -V_{zk}$.

For example, if the zener breakdown voltage of a junction diode is $V_{zk} = 37V$ then, when in **breakdown**, that junction diode will exhibit a voltage of $V_D = -37V$.

**Q:** What about this parameter $V_T$? Why did you not include it among the three device parameters?

**A:** The thermal voltage $= V_T$ is not a device parameter, it is a physical parameter.
**Lots of physics**

Specifically, the thermal voltage is determined from three important physical values:

\[ V_T = \text{Thermal Voltage} = \frac{kT}{q} \]

Where:

- \( k \) = Boltzman’s Constant
- \( T \) = Diode Temperature \( (^\circ K) \)
- \( q \) = Charge on an electron (coulombs)

At room temperature (approximately 20 \(^\circ C\)), we find the thermal voltage has a value of:

\[ V_T \approx 25 \text{ mV at } 20 \text{ } ^\circ C, \]

**IMPORTANT NOTE!**: Unless otherwise stated, we will assume that each and every junction diode is at room temperature (i.e., \( T = 20 \text{ } ^\circ C \)).

Thus, we will almost always assume that the thermal voltage \( V_T \) of all junction diodes is 25 mV (i.e., \( V_T = 25 \text{ mV} \))!
Q: The junction diode equation appears to be conditional—it includes the statement:

“for \( v_D > -V_{ZK} \)”

A: That’s correct; the equation is not valid in the breakdown region!
Correct for almost everything!

Q: So you’re saying that the equation:

\[ i_D = I_s \left( e^{\frac{V_D}{kT}} - 1 \right) \]

is valid for both the reverse and forward bias regions?

A: Both those regions—and the transition region between them!!!!

This junction diode equation is valid for any and all junction diode voltages that are significantly larger than \(-V_{ZK}\).
This first term is diffusion current

Now, let’s look closer at the equation:

\[ i_D = I_s \left( e^{\frac{\nu_D}{nV_T}} - 1 \right) \]

We rewrite it explicitly with two terms:

\[ i_D = I_s e^{\frac{\nu_D}{nV_T}} - I_s \]

These two terms each have a very important physical meaning.

The first term is called the diffusion current \( i_{\text{diff}} \):

\[ i_{\text{diff}} = I_s e^{\frac{\nu_D}{nV_T}} \]

Note that diffusion current is a function of junction diode voltage \( \nu_D \).
The second is drift current

The second term is called the drift current \( i_{\text{drift}} \):

\[
i_{\text{drift}} = -I_s
\]

Three things to note about drift current:

1. Drift current is **negative**—it flows from cathode to anode!

2. Drift current is **very small** (e.g., nano-amps or smaller).

3. Drift current is a **constant**—it is independent of junction diode voltage \( v_D \)!

Thus, we can express *junction diode current* as:

\[
i_D = i_{\text{diff}} + i_{\text{drift}}
\]

\[
= I_s e^{\frac{v_D}{nVR}} - I_s
\]
Consider diffusion current

Now let’s examine diffusion current, as it very much depends on diode voltage!

Let’s consider three cases:

1. the junction diode voltage is several times lower (i.e., more negative) than the thermal voltage $V_T = 0.025 \, V$. I.E.:

$$\frac{V_D}{V_T} = \frac{V_D}{0.025} \ll -1$$

2. the junction diode voltage is zero.

3. the junction diode voltage is several times higher (i.e., more positive) than the thermal voltage $V_T = 0.025 \, V$. I.E.:

$$\frac{V_D}{V_T} = \frac{V_D}{0.025} \gg 1$$
If the voltage is negative

Note that the diffusion current is exponentially related to the junction diode voltage:

\[ i_{\text{diff}} = I_s e^{\frac{v_D}{nV_T}} \]

Now for the first case, where the junction diode voltage is negative by a value several times the thermal voltage.

Let's assume, for example, that the junction diode voltage is:

\[ v_D = -10V_T = -0.25V \]

This voltage is barely "south of" zero, yet look what it does to diffusion current (assume \( n = 1 \)):

\[ i_{\text{diff}} = I_s e^{\frac{-10V_T}{V_T}} = I_s e^{-10} \]
Almost no diffusion current!

Remember, scale current \( I_s \) is a really small value, and \( e^{-10} \) is likewise a really small value.

The product of a really small number and another really small number is a really, really small number!!

In other words, the diode diffusion current is essentially zero if the junction diode voltage is negative!

Thus, for this first case, we find that the junction diode current is:

\[
i_D \approx 0 + i_{drift} = i_{drift} = -I_s \quad \text{for} \quad \frac{V_D}{V_T} \ll -1
\]

Thus, there is a tiny amount of current flowing from cathode to anode!
Smells like the reverse bias region

Q: Hey! You said that there was the same tiny amount of negative current flowing when in the reverse bias "region"!

A: That’s right!

And in the reverse bias region, the diode voltage is negative.

This case describes the reverse bias region—the diffusion current is zero.
Voltage is zero

For the **second case** (where the diode voltage is zero), we find that the **diffusion** current is:

\[ i_{\text{diff}} = I_s e^{\frac{0}{VT}} = I_s e^0 = I_s \]

When \( v_D = 0 \), the **diffusion** current is **equal** to the **scale** current \( I_s \)!

**Q:** Wow!

**Current flows through a junction diode when no voltage is placed across it?**

**A:** Not so fast my friend!
The currents cancel

When the junction diode voltage is zero, we find that the diffusion current is non-zero:

\[ i_{\text{diff}} = I_s \]

And of course the drift current (being independent of \( V_D \)) is its non-zero value:

\[ i_{\text{drift}} = -I_s \]

But the diode current \( i_D \) is the sum of these two currents:

\[ i_D = i_{\text{diff}} + i_{\text{drift}} = I_s - I_s = 0 \quad \text{for} \quad V_D = 0 \]

The diffusion current for this case is “equal but opposite” the drift current—the net result is no current flow!
Voltage is positive

Now, for the final case, the junction diode voltage is several times larger (more positive) than the thermal voltage.

Let's assume (for example) that:

\[ V_D = +10 \text{ V} \quad V_T = +0.25 \text{ V} \]

The resulting diffusion current is:

\[ i_{\text{diff}} = I_s e^{\frac{V_D}{V_T}} = I_s e^{+10} \]

Note that \( e^{+10} \) is a very big number!

As a result, the magnitude of the diffusion current is orders-of-magnitude larger than drift current \( |i_{\text{diff}}| \gg |i_{\text{drift}}| \), such that we can ignore the drift current term:

\[ i_D = i_{\text{diff}} + i_{\text{drift}} \approx i_{\text{diff}} = I_s e^{\frac{V_D}{nV_T}} \quad \text{for} \quad \frac{V_D}{V_T} \gg 1 \]
How do we make diffusion current large?

Q: So you’re saying the diffusion current is very large?

A: Nope!

Remember the scale current $I_s$ is exceedingly small (e.g., pico-amps).

Thus for this example ($V_D = +0.25\, V$), we find that although the resulting diffusion current is many orders-of-magnitude larger than $I_s$, it is still not particularly significant.

Q: Yikes!

Is there no way to get a significant junction diode current?

A: Note we used as our example $V_D = +0.25\, V$, this voltage is just slightly “north” of zero!

Let’s continue to increase the junction diode current and see what happens!
That woman used to terrify me

Example: $I_s = 10^{-13} A$, $n = 1$

<table>
<thead>
<tr>
<th>$V_D$ [Volts]</th>
<th>$I_D$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td>0.9 $\mu$A</td>
</tr>
<tr>
<td>0.5</td>
<td>0.05 mA</td>
</tr>
<tr>
<td>0.6</td>
<td>2.6 mA</td>
</tr>
<tr>
<td>0.7</td>
<td>140 mA</td>
</tr>
<tr>
<td>0.8</td>
<td>7.9 A</td>
</tr>
<tr>
<td>0.9</td>
<td>431.1 A</td>
</tr>
</tbody>
</table>

$I’’m$ melting!

Look closely at what occurred!

At $V_D = 0.5 V$, the diode current was an insignificant 50 $\mu$A.

Yet, when the junction diode voltage is increased by just another 400 mV—to a value $V_D = 0.9 V$—the junction diode current increases to an implausible 431 Amps!
Some surprisingly useful approximations

Therefore, we conclude that a junction diode with “significant” but “plausible” current will exhibit a diode voltage in the narrow region between “about” 600 and 800 mV:

\[ 0.6 \, V < v_D < 0.8 \, V \quad \text{for significant yet plausible } i_D \]

Q: That’s not much of variation; why don’t we just call it \( v_D = 0.7 \, V \) and be done with it?

A: We often do just exactly that!

A simple but surprisingly accurate approximation for the forward bias region of a junction diode is:

\[ v_D \approx 0.7 \, V \quad \text{for significant yet plausible } i_D \]
Don’t forget: It’s an APPROXIMATION!

Some important things to note about this approximation:

1. It’s just an approximation!

   The junction diode voltage is not exactly 700 mV, it’s just somewhere near (i.e., ±100 mV) this value.

   If the diode current is relatively small, then the junction diode voltage will be slightly less than 0.7 V; relatively large, and it will be slightly more than 0.7 V.

2. This is a subjective approximation.

   Some engineers (and text books) use a value of 0.65 V, while others might use 0.6 V or 0.75 V.
The Junction Diode
Forward Bias Equation

For the forward bias region, we have learned that the diode current $i_D$ can be related to the diode voltage $v_D$ using the following approximation:

$$i_D = I_S \left( e^{\frac{v_D}{nV_T}} - 1 \right) \approx I_S e^{\frac{v_D}{nV_T}},$$

provided that $v_D/V_T \gg 1$.

An advantage of this approximation is that we can easily invert it, so that we can express voltage $v_D$ in terms of junction diode current $i_D$:

$$I_S e^{\frac{v_D}{nV_T}} = i_D$$

$$e^{\frac{v_D}{nV_T}} = \frac{i_D}{I_S}$$

$$\frac{v_D}{nV_T} = \ln \left( \frac{i_D}{I_S} \right)$$

$$v_D = nV_T \ln \left( \frac{i_D}{I_S} \right)$$
You remember: \[ \log(x) - \log(y) = \log(x/y) \]

Now, say a voltage \( v_D = V_1 \) across some junction diode results in a current \( i_D = I_1 \).

Likewise, a different voltage \( v_D = V_2 \) across this very same diode will (of course) result in a different current \( i_D = I_2 \).

We can define the difference between these two voltages as \( \Delta v_D = V_2 - V_1 \), and then using the “inverted” forward bias equation to express this voltage difference as:

\[
\Delta v_D = V_2 - V_1 = nV_T \ln \left( \frac{I_2}{I_S} \right) - nV_T \ln \left( \frac{I_1}{I_S} \right)
\]

\[
= nV_T \ln \left( \frac{I_2}{I_1} \right)
\]
Where the heck did $I_s$ go?

Yikes! Look at what this equation says: $\Delta V_D = nV_T \ln \left( \frac{I_2}{I_1} \right)$

* The difference in the two voltages is dependent on the ratio of the two currents.

* This voltage difference is independent of scale current $I_s$.

For example, say that the second current is 10 times the first:

$$I_2 = 10I_1$$

Assuming $n = 1$, we find that the difference in junction diode voltage is:

$$\Delta V_D = nV_T \ln \left( \frac{I_2}{I_1} \right) = V_T \ln(10) = 0.058V$$

Think about what this means!
58mV per decade

It means that each time we increase the junction diode current one whole order-of-magnitude, the junction diode voltage increases just a measly 58 mV!

Thus, if a junction diode with a voltage $v_D = 0.6 \, V$ exhibits a current of 1.0 mA, we can quickly determine the diode voltage for a current of 10mA, 100 mA, 1.0 A and 10.0 A:

<table>
<thead>
<tr>
<th>$i_D , (mA)$</th>
<th>$v_D , (V)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>0.6</td>
</tr>
<tr>
<td>10.0</td>
<td>0.658 = 0.6 + (1)0.058</td>
</tr>
<tr>
<td>100.0</td>
<td>0.716 = 0.6 + (2)0.058</td>
</tr>
<tr>
<td>1,000.0</td>
<td>0.774 = 0.6 + (3)0.058</td>
</tr>
<tr>
<td>10,000.0</td>
<td>0.832 = 0.6 + (4)0.058</td>
</tr>
</tbody>
</table>
We can likewise invert the above equation and express the ratio of the two currents in terms of the difference of the two voltages:

\[ nV_T \ln \left( \frac{I_2}{I_1} \right) = V_2 - V_1 \]

\[ \ln \left( \frac{I_2}{I_1} \right) = \frac{V_2 - V_1}{nV_T} \]

\[ \frac{I_2}{I_1} = \exp \left[ \frac{V_2 - V_1}{nV_T} \right] \]

Again, we find that this expression is independent of scale current \( I_s \)!

Note that we can alternatively express these equations as:

\[ V_2 = V_1 + nV_T \ln \left( \frac{I_2}{I_1} \right) \]

and

\[ I_2 = I_1 \exp \left[ \frac{V_2 - V_1}{nV_T} \right] \]

Q: Stop wasting our time with these pointless derivations!

A: On the contrary, these expressions are often very useful!
The test point—as good as knowing $I_s$

Frequently, instead of explicitly providing device parameters $n$ and $I_s$, a junction diode is specified by stating $n$, and then one specific test point for that diode.

A “test point” is simply one current ($i_D = I_{test}$) and the corresponding diode voltage measurement ($v_D = V_{test}$) from that junction diode.

For example, a junction diode might be specified as:

"A junction diode with $n = 1$ pulls 2mA of current at a diode voltage 0.6 V."

In other words, we are given the test point $I_{test} = 2.0 \text{ mA}$ and $V_{test} = 0.6 \text{ V}$.

The above statement completely specifies the performance of this particular junction diode—we can now determine the current flowing through this diode for any other value of diode voltage $v_D$.

Likewise, we can find the voltage across the diode for any other diode current value $i_D$. 
**You’re welcome!**

**Q:** Just how do we do that?

**A:** Using the “pointless” expressions derived earlier, where $I_1 = I_{test}$ and $V_1 = V_{test}$, we can find these alternate forward bias expressions:

$$v_D = V_{test} + nV_T \ln \left( \frac{i_D}{I_{test}} \right)$$

and

$$i_D = I_{test} \exp \left[ \frac{v_D - V_{test}}{nV_T} \right]$$

Note that neither expression involves $I_s$!

So for example, say we wish to find the current through the junction diode specified above when a potential difference of $v_D = 0.7$ V is placed across it.

We have two options for finding this current...
Option 1: Find $I_s$ first

We know that $n = 1$ and that $i_D = 2.0 \ mA$ when $v_D = 0.6 \ V$.

Thus, we can use this information to solve for scale current $I_s$:

$$I_s e^{\frac{v_D}{nV_T}} = i_D$$

$$I_s e^{\frac{0.6}{0.025}} = 2$$

$$I_s = 2 e^{\frac{-0.6}{0.025}}$$

$$I_s = 7.55 \times 10^{-11} \ mA$$

Now, we use the forward-biased junction diode equation to determine the current through this device at the new voltage of $v_D = 0.7 \ V$:

$$i_D = I_s e^{\frac{v_D}{nV_T}}$$

$$= (7.55 \times 10^{-11}) e^{\frac{0.7}{0.025}}$$

$$= 109.2 \ mA$$
Option 2: Use the test point directly!

Here, we directly determine the current at $v_D = 0.7$ using one of the expressions derived earlier in this handout!

Using the test point $I_{test} = 2.0 \ mA$ and $V_{test} = 0.6 \ V$, we can state the relationship between current $i_D$ as and voltage $v_D$ as:

$$i_D = I_{test} \ exp\left[\frac{v_D - V_{test}}{nV_T}\right] = 2.0 \ exp\left[\frac{v_D - 0.6}{nV_T}\right] \ mA$$

For $v_D = 0.7 \ V$ we can therefore find current $i_2$ as:

$$i_2 = 2.0 \ exp\left[\frac{0.7 - 0.6}{0.025}\right] = 109.2 \ mA$$

Option 2 (using the equations we derived in this handout) is obviously quicker and easier (note in option 2 we did not have to deal with annoying numbers like $7.55 \times 10^{-11}$!).
Often then just assume you know that \( n = 1 \) and \( V_{test} = 0.7 \text{ V} \)

Finally, we should also note that junction diodes are often specified simply as “a 2mA diode” or “a 10 mA diode” or “a 100 mA diode”.

These statement implicitly provide the diode current at the standard diode test voltage of \( V_{test} = 0.7 \text{ V} \).

Q: But what about the value of junction diode ideality factor \( n \)?

A: If no value of \( n \) is provided (and there is not sufficient information given to determine it), we typically just assume that \( n =1 \).
For example, consider the following problem:

"Determine the voltage across a **100 mA junction diode** when there is 2 mA of current flowing through it."

A **"100 mA junction diode"** simply means a junction diode that will have a current of 100 mA flowing through it ($i_D = 100$ mA) if the voltage across it is $v_D = 0.7$ V.

We will assume that $n = 1$, since no other information about that parameter was given.

Thus, using $V_{test} = 0.7$ V, $I_{test} = 100$ mA, we can determine the diode voltage $v_D$ when $i_D = 2.0$ mA:

\[
v_D = V_{test} + n V_T \ln \left( \frac{i_D}{I_{test}} \right)
\]

\[
= 0.7 + (0.025) \ln \left( \frac{2}{100} \right)
\]

\[
= 0.7 - 0.10
\]

\[
= 0.60 V
\]

*Why, these expressions are not pointless at all.*

*They turn out to be—EXCELENT!*
### Example: A Junction Diode Circuit

Consider the following circuit with two junction diodes:

![Circuit Diagram]

The diodes are identical, with \( n = 1 \) and \( I_S = 10^{-14} \) A.

**Q:** If the current through the resistor is 6.5 mA, what is the voltage of source \( V_S \)?

**A:** This is a difficult problem to solve! Certainly, we cannot just write:

\[
V_S = \ldots
\]

and then the answer. Instead, let’s just determine what we can, and see what happens!
1) If 6.5 mA flows through a 0.1 K resistor, we find from Ohm's law that the voltage across that resistor is:

\[ v_R = i_R R = (6.5) 0.1 = 0.65 V \]

2) If the voltage across the resistor is 0.65 V, then the voltage across the diode \( D_2 \), which is parallel to the resistor, can be determined from KVL to be the same value:

\[ v_{D2} = v_R = 0.65 V \]
3) If we know the voltage across a p-n junction diode, then we also know its current!

\[ i_{d2} = I_s \exp \left( \frac{V_{d2}}{nV_T} \right) = 10^{-14} \exp \left( \frac{0.650}{0.025} \right) = 1.96 \text{ mA} \]

4) If we know \( i_{d2} \) and the current \( i_R \) through the resistor, we likewise know (using KCL) the current through \( D_1 \):

\[ i_{d1} = i_R + i_{d2} = 6.5 + 1.96 = 8.46 \text{ mA} \]
5) If we know the current through a junction diode, then we can find the voltage across it:

\[ v_{D1} = nV_T \ln \left( \frac{i_{D1}}{I_S} \right) = 0.025 \ln \left( \frac{0.00846}{10^{-14}} \right) = 0.69V \]

6) Finally, if we know \( v_{D1} \) and \( v_{D2} \), we can find \( V_S \) using KVL:

\[ V_S = v_{D1} + v_{D2} = 0.69 + 0.65 = 1.34V \]
Diode Power Dissipation

We know that for a two-terminal device, the absorbed power is simply equal to the product of the voltage across and current through the device:

\[ P_A = V I \]

For this notation, a positive result is the power absorbed by the device, so that a negative value indicates that the device is a source of power!

As a result, the power absorbed by a junction diode is:

\[ P_A = V_D I_D \]
It's not a device equation!

Q: Wait a second!

I know that this is the "right equation" for a resistor; is it just a coincidence that it also "works" for a junction diode?

A: The fact that the absorbed power is the product of the current through and voltage across a two-terminal device is one that is independent of that device—it is not a device equation!

When some charge $Q$ moves through the device—any device—from one terminal to the other, the potential energy of this charge either decreases or increases.
Volts: Joules per Coulomb

Q: *Buy how much does its energy increase or decrease?*

A: That’s what the *voltage* across the device (e.g., $V_D$) *tells us*!

*Remember*, the units of volts is *Joules/Coulomb*—the change in potential *energy* for every *Coulomb* of charge!

So, for *example*, if a device voltage is *3.0 volts*, then when one *Coulomb* of charge passes from the plus terminal to the minus terminal, its *potential energy* will be *reduced by 3.0 Joules*!

Or more *generally*, if a charge $Q$ moves through a device with voltage $V$ across it, the *potential energy* of that charge will be *changed* by an amount equal to the product $QV$.

$\Delta \mathcal{E} = QV$
**Makes the device nice and toasty**

**Q:** Yikes! Just where does that energy go?

*Conservation of energy says it must go somewhere!*

**A:** That’s exactly correct!

The reduction in potential energy must be “absorbed” by the device.

This absorbed energy must then be **dissipated** (changed into another form) in some manner.

*Generally speaking, this absorbed energy is turned into heat!*
Trust me; just don’t arrive late

Q: But how do we know the amount of charge $Q$ that moves through the device?

A: Charge move through the device at a continual rate—a rate defined as Coulombs/second.

Of course this rate of charge flow (in C/s) is otherwise known as current $I$ (in Amps)!

Thus, the product of Volts and Current flow thus provides us with the rate of energy absorption:

$$V \left( \frac{Joules}{Coulomb} \right) \cdot I \left( \frac{Coulombs}{second} \right) = V \cdot I \left( \frac{Joules}{second} \right)$$
The difference between miles and miles/hour

Q: Joules per second?

I thought we were talking about energy (in just Joules)!

A: The product of $V$ and $I$ provides us with the rate at which the device—any device—must absorb energy.

Just like the rate of current flow is Coulombs/sec, this provides us with the rate of energy flow is Joules/sec.

We of course call this rate of energy flow, power.

$$1 \text{ Watt} = 1 \frac{\text{Joules}}{\text{second}}$$

So let’s consider all this with respect to diodes.
The ideal diode is just so ideal!

First let's look at an ideal diode:

\[ P_A = V_D^i I_D^i \]

If in forward bias, we know that the ideal diode voltage is zero \((V_D^i = 0)\), so that the absorbed power is likewise zero!

\[ P_A = (0) I_D^i = 0 \]

And, in reverse bias, we know that the ideal diode current is zero \((I_D^i = 0)\), so that the absorbed power is as well!

\[ P_A = V_D^i (0) = 0 \]

→ An ideal diode absorbs no energy—yet another characteristic that makes this device ideal!
Forward Bias region is nice and warm

Q: What about junction diodes?

A: If a junction diode is operating in the forward bias region, then we know that:

a) the diode voltage is within a few hundred milli-volts of 0.7V.

b) the diode current is “significant yet plausible”.

As a result, we find that a junction diode operating in the forward bias region will absorb energy at some “moderate” rate!

\[ P_A \approx 0.7I_D \]
Cooler than the other side of the pillow

If a junction diode is operating in the reverse bias region, we know that:

a) The diode current will be negative and extremely small.

b) The diode voltage will be negative.

As a result, we find that a junction diode operating in the reverse bias region will absorb energy at an extremely small rate—essentially zero!

\[ P_A = V_D (-I_s) \approx 0 \]
Houston, we have a problem

If a junction diode is operating in the breakdown region, we know that:

a) the diode current will be negative, and will be significant.

b) The diode voltage will be a large, negative value \(-V_{ZK}\).

As a result, we find that a junction diode operating in the breakdown region might absorb energy at a very large rate!

\[ P_A = -V_{ZK} I_D > 0 \]

Q: Is this bad?

A: It can be!

A junction diode (or any device, for that matter) absorbing energy at a large rate must then dissipate this energy at a large rate—it must dissipate the heat created!
I’m melting!

**Q:** Why, what happens if it doesn’t?

**A:** If energy is absorbed faster than the heat is dissipated, the temperature of the device will rise.

If equilibrium is not reached—if the rate of heat dissipation does not become equal to the rate of energy absorption—then the device will quite literally “go up in smoke”!

Thus, breakdown is the most problematic of the three junction diode regions with respect to power dissipation—without a good thermal “sink”, our junction diode might well be destroyed!