The Blocking Diode

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Negative Resistance Zone

Negative resistance: meaning and measurement

It is a fact, verified in theory and by experiment, that no material can conduct electric current with greater efficiency than an ideal conductor having zero resistance. How, then, can the term “negative resistance” have meaning in the real world?

First, it is possible to get negative resistance readings on a DVM. If this happens, they are generally anomalous and arise because the DVM settings are incorrect. Selecting the incorrect range on a DVM can result in the use of a test current that is too small. This will result in voltages too small for the DMM to measure. These small voltages will also be susceptible to other sources of errors that will offset the reading and possibly cause a negative measurement. The main sources of error include thermoelectric EMFs, offsets generated by rectification of RFI (radio frequency interference), and offsets in the voltmeter input circuit.

But it is, in fact, possible for a semiconductor device to exhibit a negative resistance. To see why we must first look at a standard resistor. In this modest component, there is a proportional relationship between the current passing through and the voltage applied to the (usually) two terminals. In contrast, a device that exhibits negative resistance is characterized by the applied voltage and measured current being inversely proportional, defying Ohm’s law.

You can connect the terminals of a standard probe across an energized negative resistance device and plug the probe output into the analog input of an oscilloscope. Simultaneously, you can connect a current probe that senses the magnetic field associated with either of the conductors to a different analog channel input. Displaying these signals together, the waveform amplitude relations are seen to vary for different portions of the phase. An understanding of this relationship is critical to seeing how conservation laws are not violated. That is because the negative differential resistance region does not occupy the entire phase.

If voltage is applied to a load with positive resistance, power transfers from the source to the load. Transfer of power in the case of positive resistance is a one-way path – from the power source to the load. Current flows first through a hot wire, through the load, and back along the return conductor to the power source.

tunnel diode trace

The actual I-V curve from a germanium tunnel diode displaying negative resistance as depicted on Wikipedia.

Negative resistance can be either static or differential. Static resistance is another term for the ordinary resistance that conforms to Ohm's law. Differential resistance, also known as dynamic resistance, is the derivative of applied voltage with respect to measured current. Differential negative resistance happens when the electrical energy is in the form of alternating current.

Both dynamic and static resistance are measured in ohms, and of course, they conform to Ohm's law. Unlike a simple resistor, a negative resistance component can amplify power, even if it has only two terminals. In a transformer, any rise in voltage is at the expense of current, so power cannot be amplified.

So the overriding question is, how can a two-terminal device with no power applied from an external source actually amplify power? The answer is that this can happen only throughout one portion of the ac cycle, so the law of energy conservation is not violated.

Negative resistance does not ordinarily arise in nature. That is because power into a load is equal to the current through the load times the voltage across it. With a negative resistance, still hypothetical at this point in the discussion, instead of dissipating electrical energy in the form of heat, it would actually generate electrical energy and feel cool to the touch. The explanation for this non-intuitive state of affairs is that the voltage and current would have opposite signs. (A negative value times a positive value is a negative value.)

When voltage is applied to a passive device that exhibits negative resistance in some part of its response curve, the device outputs power, but that happens only during the period when voltage as a function of current is negative. The device outputs power when it is operating in the second and fourth quadrants of its response curve, but unfortunately for the perpetual motion community, this is only power that is stored when the device operates in the first and third quadrants.

A statement that defines one aspect of negative resistance is that those few devices that exhibit it experience a drop in current as more voltage is applied across their terminals. This behavior is opposite to that of a standard positive resistance, where voltage and current vary directly. Accordingly, a two-terminal device can be made to amplify an ac signal applied at the terminals. Examples are tunnel diodes and Gunn diodes.

tunnel diode curves

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Negative resistance in a tunnel diode arises because there are three components to the diode current. First is normal diode current through a PN junction diode. Tunnelling current: This is the current that arises as a result of the tunnelling effect. Excess current: This is a third element of current that contributes to the overall current within the diode. It results from what may be termed excess current that results from tunnelling though bulk states in the energy gap, and means that the valley current does not fall to zero.

Tunnel diodes, first manufactured by Sony in 1957, have negative differential resistance within a prescribed operating range. They employ a quantum mechanical effect known as quantum tunneling, which lets them operate as negative resistances at high frequencies, well into the microwave region.

Like all diodes, tunnel diodes have a PN region. But it is heavily doped and unusually narrow. This creates a band gap in which conduction band electron states on the N side align with valence band hole states on the P side.

The prevalent semiconducting material used in tunnel diodes is germanium. Gallium arsenide and silicon are alternatives. Because tunnel diodes have negative differential resistance in a portion of their operating range, they are used in frequency converters and detectors. The explanation for negative resistance in a tunnel diode is that when the diode is forward biased, a rising applied voltage lets electrons tunnel through the P-N junction because it is quite narrow, typically 10 nm.

When forward bias voltage is low, the conduction states on either side of the junction barrier are closely aligned. But as this voltage rises, the conduction states on either side become misaligned.

For this reason, the current flow drops as the voltage rises, giving the device a negative resistance differential. As still higher voltage is applied, operation shifts from tunneling to the normal diode mode. What is unique in a tunneling diode is its reverse-bias operation, where the device is a fast rectifier with no offset voltage and highly linear behavior.

tunnel symbols

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The tunneling diode, when forward biased, exhibits quantum mechanical tunneling. Boosting forward voltage causes forward current to drop, and this exemplifies negative resistance. These qualities make the device suitable for low-noise microwave applications. In the past they were also used in oscilloscope triggering circuits. In recent years, the FET and other non-diode, three-terminal devices have replaced tunneling diodes, notably in local oscillators for superheterodyne receivers.

gunn diode junction

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The Gunn diode is another component that exploits negative resistance. It is also known as a transferred electron device, another high-frequency component, currently found in law-enforcement speed detection equipment, commercial door openers and microwave relay links. Most diodes have P- and N-doped layers, but Gunn diodes employ N-doped regions exclusively. Unlike other diodes, Gunn devices do not conduct directionally, which means that they cannot function as rectifiers. There are three active layers, two N-doped with a thin N-doped region situated in the middle. In normal operation this middle layer exhibits the greatest voltage drop. As higher voltage is applied, the Gunn diode becomes a negative-resistance device. Accordingly, the Gunn diode in this mode operates as an RF amplifier. When dc voltage is applied, the diode goes into oscillation, making it useful in other high-frequency applications.

gunn diode symbol

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Gunn diodes are used at the highest frequencies. Among

devices that exploit negative resistance, they are noted for high output power. Gunn diodes have applications that include anti-lock brakes, radar for aircraft collision avoidance, amateur radio transmission, security alarms and radio astronomy.

Electric discharge lighting such as neon and fluorescent fixtures are common devices exhibiting negative resistance. A heavy voltage drop due to utility power applied across the terminals could cause a fluorescent bulb to rupture, so for this reason, a ballast, mounted inside or outside the enclosure serves to mitigate the effects of negative resistance.

Power sources for negative resistance components include batteries, solar arrays, fuel cells, generators and transistors. Negative resistance applications, besides those mentioned above, include active resistors and, where positive feedback is installed, feedback oscillators, negative impedance converters and active filters.

The behavior of negative resistance circuitry is complex, sometimes difficult to understand, because of the way it appears to operate contrary to common sense. Being nonlinear, negative resistance actually varies with the applied voltage, and that is sometimes hard to deal with. But as functioning components, negative resistance devices conduct electricity and permit the circuits in which they appear to do work and play useful roles in contemporary circuit designs.

PIV - Peak Inverse Voltage

What is PIV rating in a diode?

PIV stands for **‘Peak Inverse Voltage’**. It refers to the maximum reverse bias voltage a semiconductor diode or other semiconductor devices can withstand without damaging themselves. The peak inverse voltage is also known as **peak reverse voltage.**

PIV rating of a diode is temperature-dependent. It increases with an increase in temperature and decreases with a decrease in temperature. Peak Inverse voltage rating is determined by the manufacturer. A typical diode used in rectifiers has a PIV rating of at least 50Vdc at room temperature. However, diodes with high peak inverse voltage ratings of thousands of volts are also available in the market.

What happens if the PIV rating of a diode is exceeded?

If the applied reverse bias voltage is too great that it exceeds the rated peak reverse voltage, avalanche breakdown may occur in the diode. This can permanently damage the diode.

PIV rating

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Source: Wikipedia. The voltage corresponding to point marked ‘knee’ is called the peak inverse voltage.

Further reference: https://www.mouser.in/datasheet/2/308/MMBD1405-D-1811593.pdf

Fast Recovery Diodes

What are Fast Recovery Diodes (FRD)?

This diode with a p-n junction is designed to make the reverse recovery time (trr) smaller and is also called a high-speed diode. Compared to general rectifying diodes, the trr is 2 to 3 digits smaller because the FRD is designed with a switching power supply to rectify high frequencies of tens of kHz or hundreds of kHz.

Typical characteristics

Withstand voltage (V_{RM})	High voltages such as 600 V, 800 V and 1000 V
Forward voltage (V_F)	Approximately 1.3 to 3.6 V
Reverse current (I_R)	Extremely small from several µA to tens of µA
Reverse recovery time (trr)	Approximately tens of nS to 100 nS
Application	Rectifying high voltage switching circuits (such as PFC)

It is necessary to select and use the best type of diode according to each application, because the smaller the reverse recovery time is made, the larger the V_F becomes.

Recovery characteristics of diode

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One can equate trr to the “time for the holes to come back” because hole movement takes more time when compared to electron movement.

Relationship between forward current (I_F) and reverse recovery time (trr)

When forward current is small

When forward current is small

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When forward current is large

When forward current is large

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How to improve trr

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Heavy metal is diffused or an electron beam is irradiated onto the diode with a p-n junction to create a carrier trap in order to catch holes while they are going back. The trr is improved by 2 to 3 digits, but the V_F becomes larger as a result.

A diode with this countermeasure is referred to as a high-speed diode and is generally called an FRD (Fast Recovery Diode).

- Product List "Fast recovery diodes"

Selecting and Using Fast Recovery Diodes

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V_F-trr trade-off for diodes that withstand 600 V

General rectifying diodes

These p-n diodes are not high-speed. The trr is large, but the V_F is small, around 1 V (for 600 V products). These diodes are designed for commercial frequencies, such as 50/60 Hz, and are not used on a switching circuit.

FRD

FRD stands for fast recovery diodes. They offer high-speed support and generally have a trr of approximately 50 to 100 ns. With a V_F of approximately 1.5 V, it is rather large when compared to general rectifying diodes.
Another generic term for the FRD type would be a “High-speed diode.”

FRD (Ultra high-speed type)

Even among the fast recovery diodes, this diode is designed specifically for speed. The trr is approximately 25 ns, which is extremely small, but the V_F is quite large at 3 to 3.6 V. This diode is used in applications that specifically require high-speed. Even if the V_F is larger than this, the relative benefit of the trr is small.
This type is not just important because of its high-speed but for its soft recovery characteristics as well.

Current waveform for critical conduction mode PFC

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The diode current slowly heads to OFF as indicated by the figure. The recovery current is also restricted by the inductor and does not become so large.
In this type of application, an ultra high-speed diode is not required, and using a general FRD where the VF is not really large improves efficiency.

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trr of 600 V class high-speed diodes

- Example of ultra high-speed type
  trr = 25 nsec (max), V_F = 3.6 V (max)
- Example of high-speed type
  trr = 100 nsec (max), V_F = 1.5 V (max)

The high-speed types are appropriate for this application.

Current waveform for continuous conduction mode PFC

When used in this type of circuit, a diode with the smallest trr must be used even when sacrificing the V_F.

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As indicated by the figure, when a current flows in a diode and a reverse voltage is suddenly applied, if the current cuts off, an extremely large recovery current flows during the trr period resulting in loss.

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trr of 600 V class high-speed diodes

Example of ultra high-speed type

- trr = 25 nsec (max), V_F = 3.6 V (max)
- Example of high-speed type
  trr = 100 nsec (max), V_F = 1.5 V (max)

The ultra high-speed types above are appropriate for this application.

Soft recovery and hard recovery

When the recovery current restores too suddenly, it produces more noise. As a result, the trr must not only be small but it must restore softly or smoothly.

Numbers 1 and 3 below may appear to have the same trr in the catalogue, but both the loss and noise are quite different. In addition, the number 2 appears to be extremely good when looking at the catalogue, but it produces a large noise.

Image not found or type unknown Both power loss and noise are small	Image not found or type unknown Power loss is small but noise is large	Image not found or type unknown Both power loss and noise are large

Avalanche Diodes

Source: https://www.physics-and-radio-electronics.com/electronic-devices-and-circuits/semiconductor-diodes/avalanchediode-constructionandworking.html

What is avalanche diode?

An avalanche diode is a special type of semiconductor device designed to operate in reverse breakdown region. Avalanche diodes are used as relief valves (a type of valve used to control the pressure in a system) to protect electrical systems from excess voltages.

Construction of avalanche diode

Avalanche diodes are generally made from silicon or other semiconductor materials. The construction of avalanche diode is similar to zener diode but the doping level in avalanche diode differs from zener diode.

Zener diodes are heavily doped. Therefore, the width of depletion region in zener diode is very thin. Because of this thin depletion layer or region, reverse breakdown occurs at lower voltages in zener diode.

On the other hand, avalanche diodes are lightly doped. Therefore, the width of depletion layer in avalanche diode is very wide compared to the zener diode. Because of this wide depletion region, reverse breakdown occurs at higher voltages in avalanche diode. The breakdown voltage of avalanche diode is carefully set by controlling the doping level during manufacture.

Symbol of avalanche diode

The symbol of avalanche and zener diode is same. Avalanche diode consists of two terminals: anode and cathode. The symbol of avalanche diode is shown in below figure.

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The symbol of avalanche diode is similar to the normal diode but with the bend edges on the vertical bar.

How avalanche diode works?

A normal p-n junction diode allows electric current only in forward direction whereas an avalanche diode allows electric current in both forward and reverse directions. However, avalanche diode is specifically designed to operate in reverse biased condition.

Avalanche diode allows electric current in reverse direction when reverse bias voltage exceeds the breakdown voltage. The point or voltage at which electric current increases suddenly is called breakdown voltage.

When the reverse bias voltage applied to the avalanche diode exceeds the breakdown voltage, a junction breakdown occurs. This junction breakdown is called avalanche breakdown.

When forward bias voltage is applied to the avalanche diode, it works like a normal p-n junction diode by allowing electric current through it.

When reverse bias voltage is applied to the avalanche diode, the free electrons (majority carriers) in the n-type semiconductor and the holes (majority carriers) in the p-type semiconductor are moved away from the junction. As a result, the width of depletion region increases. Therefore, the majority carriers will not carry electric current. However, the minority carriers (free electrons in p-type and holes in n-type) experience a repulsive force from external voltage.

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As a result, the minority carriers flow from p-type to n-type and n-type to p-type by carrying the electric current. However, electric current carried by minority carriers is very small. This small electric current carried by minority carriers is called reverse leakage current.

If the reverse bias voltage applied to the avalanche diode is further increased, the minority carriers (free electrons or holes) will gain large amount of energy and accelerated to greater velocities.

The free electrons moving at high speed will collide with the atoms and transfer their energy to the valence electrons.

The valance electrons which gains enough energy from the high-speed electrons will be detached from the parent atom and become free electrons. These free electrons are again accelerated. When these free electrons again collide with other atoms, they knock off more electrons.

Because of this continuous collision with the atoms, a large number of minority carriers (free electrons or holes) are generated. These large numbers of free electrons carry excess current in the diode.

When the reverse voltage applied to the avalanche diode continuously increases, at some point the junction breakdown or avalanche breakdown occurs. At this point, a small increase in voltage will suddenly increases the electric current. This sudden increase of electric current may permanently destroys the normal p-n junction diode. However, avalanche diodes may not be destroyed because they are carefully designed to operate in avalanche breakdown region.

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The breakdown voltage of the avalanche diode depends on the doping density. Increasing the doping density will decreases the breakdown voltage of the avalanche diode.

Applications of avalanche diodes

- Avalanche diodes can be used as white noise generators.
- Avalanche diodes are used in protecting circuits.

Types of Diodes

The various types of diodes are as follows:

1. Zener diode
2. Avalanche diode
3. Photodiode
4. Light Emitting Diode
5. Laser diode
6. Tunnel diode
7. Schottky diode
8. Varactor diode
9. P-N junction diode