Tunnel diode:

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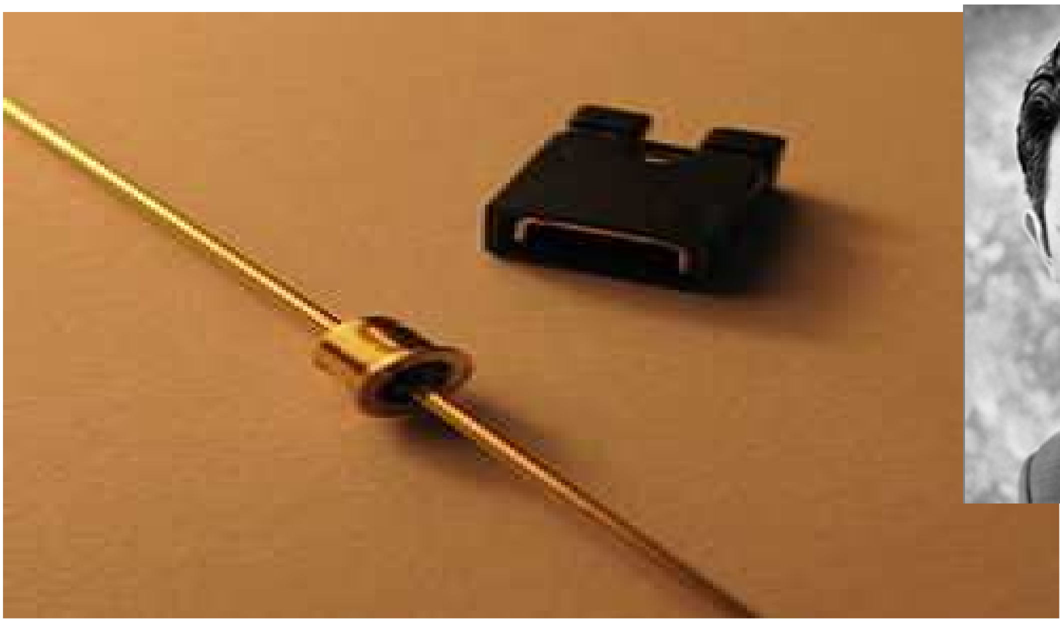



1N3716 tunnel diode (with jumper for scale)

A **tunnel diode** or **Esaki diode** is a type of semiconductor diode which is capable of very fast operation, well into the microwave frequency region, by using quantum mechanical effect called tunneling.

It was invented in August 1957 by Leo Esaki when he was with Tokyo Tsushin Kogyo, now known as Sony. In 1973 he received the Nobel Prize in Physics, jointly with Brian Josephson, for discovering the electron tunneling effect used in these diodes. Robert Noyce independently came up with the idea of a tunnel diode while working for William Shockley, but was discouraged from pursuing it.[1] These diodes have a heavily doped p–n junction only some 10 nm (100 Å) wide. The heavy doping results in a broken bandgap, where conduction band electron states on the n-side are more or less aligned with valence band hole states on the p-side. Tunnel diodes were manufactured by Sony for the first time in 1957[2] followed by General Electric and other companies from about 1960, and are still made in low volume today.[3] Tunnel diodes are usually made from germanium, but can also be made in gallium arsenide and silicon materials. They can be used as oscillators, amplifiers, frequency converters and detectors.[4]

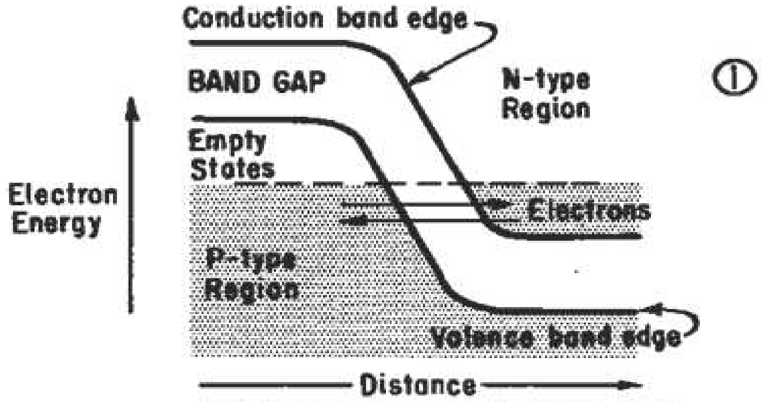
TUNNELING :

The movement of valence electrons from the valence energy band to the conduction band with little or no applied forward voltage is called tunneling.

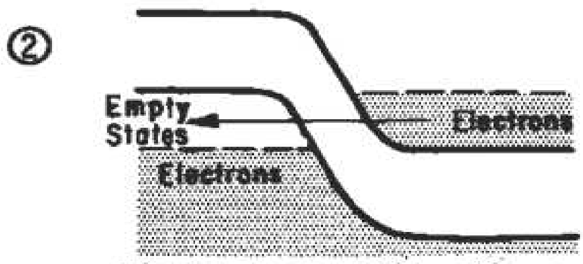
FIGURE 1

TUNNEL DIODE JUNCTION
AT VARIOUS BIAS CONDITIONS

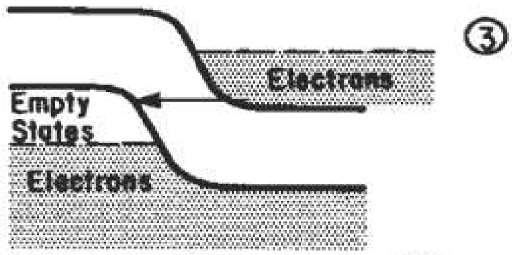
(The numbered diagrams below correspond to the numbered points on the current-voltage curve, Figure 2.)



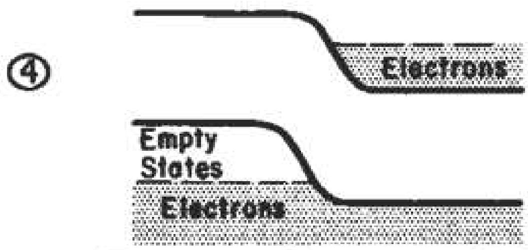
Electrons at same level on both sides of junction. No net current.



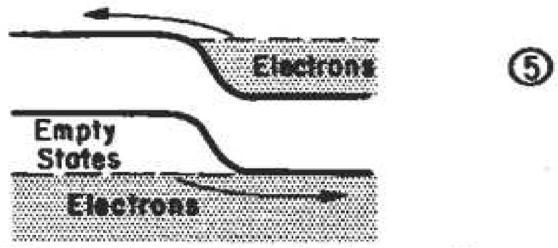
Electrons on right side are raised until they are opposite empty states on left side. Strong current flows from right to left.



Electrons on right raised still farther. Some are opposite "forbidden band gap," some opposite empty states. Current decreases.



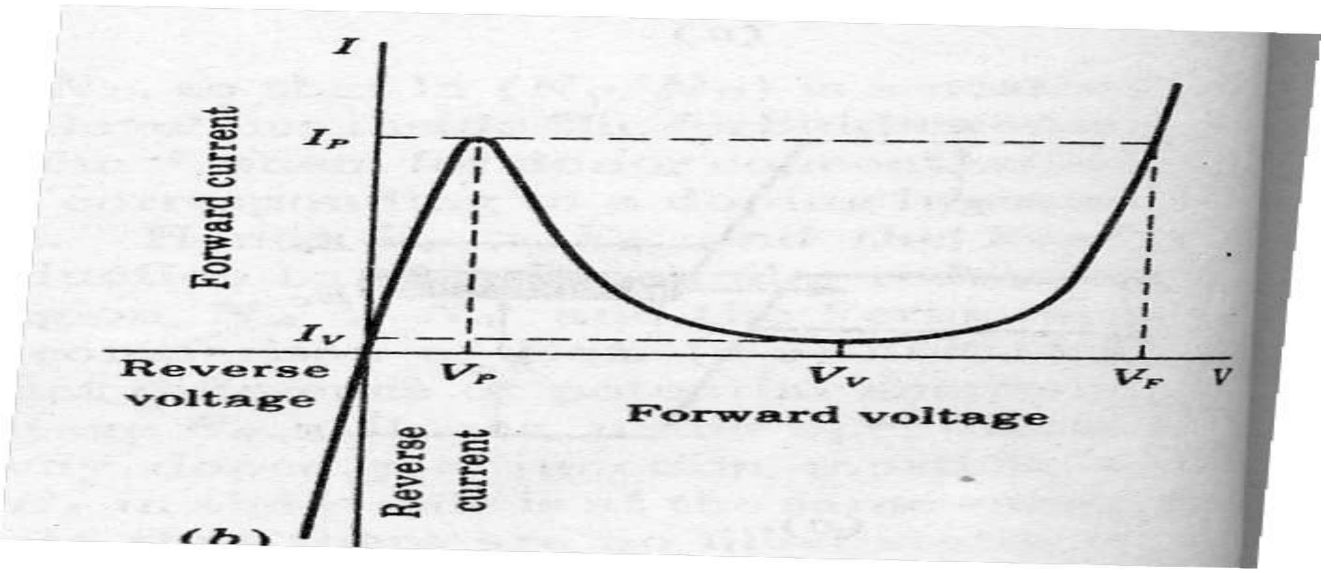
Electrons all are opposite forbidden gap. Very small current.



Electrons raised until they spill over barrier. Current increases.

Forward bias operation:

Under normal forward bias operation, as voltage begins to increase, electrons at first tunnel through the very narrow p–n junction barrier because filled electron states in the conduction band on the n-side become aligned with empty valence band hole states on the p-side of the p-n junction. As voltage increases further these states become more misaligned and the current drops – this is called *negative resistance* because current decreases with increasing voltage. As voltage increases yet further, the diode begins to operate as a normal diode, where electrons travel by conduction across the p–n junction, and no longer by tunneling through the p–n junction barrier. Thus the most important operating region for a tunnel diode is the negative resistance region.



Reverse bias operation:

When used in the reverse direction they are called **back diodes** and can act as fast rectifiers with zero offset voltage and extreme linearity for power signals (they have an accurate square law characteristic in the reverse direction).

Under reverse bias filled states on the p-side become increasingly aligned with empty states on the n-side and electrons now tunnel through the pn junction barrier in reverse direction – this is the Zener effect that also occurs in Zener diodes.

Technical comparisons:

A rough approximation of the IV curve for a tunnel diode, showing the negative differential resistance region.In a conventional semiconductor diode, conduction takes place while the p–n junction is forward biased and blocks current flow when the junction is reverse biased. This occurs up to a point known as the “reverse breakdown voltage” when conduction begins (often accompanied by destruction of the device). In the tunnel diode, the dopant concentration in the p and n layers are increased to the point where the **reverse breakdown voltage** becomes **zero** and the diode conducts in the reverse direction. However, when forward-biased, an odd effect occurs called “quantum mechanical tunnelling” which gives rise to a region where an *increase* in forward voltage is accompanied by a *decrease* in forward current. This negative resistance region can be exploited in a solid state version of the dynatron oscillator which normally uses a tetrode thermionic valve (or tube).

The tunnel diode showed great promise as an oscillator and high-frequency threshold (trigger) device since it would operate at frequencies far greater than the tetrode would, well into the microwave bands. Applications for tunnel diodes included local oscillators for UHF television tuners, trigger circuits in oscilloscopes, high speed counter circuits, and very fast-rise time pulse generator circuits. The tunnel diode can also be used as low-noise microwave amplifier.[5] However, since its discovery, more conventional semiconductor devices have surpassed its performance using conventional oscillator techniques. For many purposes, a three-terminal device, such as a field-effect transistor, is more flexible than a device with only two terminals. Practical tunnel diodes operate at a few milliamperes and a few tenths of a volt, making them low-power devices.[6] The Gunn diode has similar high frequency capability and can handle more power.

Tunnel diodes are also relatively resistant to nuclear radiation, as compared to other diodes. This makes them well suited to higher radiation environments, such as those found in space applications.

Applications of TUNNEL DIODES

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Dr. Hebb has told you a little about the possible applications of the improved tunnel diodes made by my colleagues and myself. I would like to elaborate a bit on this subject, and demonstrate a few selected applications. Most of what I will say is in the technical information sheet, but I would like to tell you which aspects of the tunnel diode are the most important ones for the various fields of application.

Generally speaking, the important properties of tunnel diodes from the electronic-circuit point of view are:

1. Extreme speed (high frequency)
2. Stable characteristics that are insensitive to temperature changes
3. Modest power supply requirements
4. Ability to operate in a wide variety of critical environments
5. Low noise level
6. Simplicity - light weight - small size

These features indicate that the tunnel diode will find many applications in a large number of fields.

One of the most important of these fields will be high-speed digital computers. The reason the tunnel diode is important in this field is its high

Vest-pocket transmitter, making use of a tunnel diode, is demonstrated by Dr. Guy Suits, Vice President and Director of Research, and Dr. Jerome J. Tiemann.

speed of response when made to operate as a switch. The tunnel diode switches either on or off in a fraction of a millimicrosecond. (A millimicrosecond is one billionth of a second.)

The first demonstration I would like to show you is a scale-of-two binary counter cell. This is a bistable, flip-flop circuit that changes its state upon receipt of an appropriate input pulse.

The important thing here is not that one can do what you have seen in any particularly convenient way with tunnel diodes. What is important is that the switching can occur so fast after the input pulse has been received. When you see this circuit up close later on you will notice some relays, which are needed to boost the voltage up to where the indicator lights can operate. The low output voltage of the tunnel diode may therefore appear to be an inconvenience -- and, in some respects, it is. This, however, may turn out to be a blessing in disguise.

I say this because the low voltage means that tunnel diodes do not generate much heat, and one of the most difficult problems which plagues computer engineers is how to get rid of all the heat. As people try to pack more and more computer in a smaller and smaller space, the problem of heat dissipation becomes ever more severe. The tunnel diode may offer some help in this respect, since it can be made to consume far less power even than a transistor -- which in turn uses much less than a vacuum tube.

Another field of application is radio communication. Here the tunnel diode is important, first because of its high-frequency potential and excellent stability, and also because of its ability to operate in critical environments with modest power supply requirements. As an extra bonus, it turns out that the tunnel diode has excellent low-noise properties. At present it is surpassed in this respect only by the maser -- which requires bulky refrigeration equipment -- and by the parametric amplifier -- which requires a high-frequency oscillator (generally a klystron) in order to operate. In contrast, the tunnel diode needs only a simple direct-current supply.

Because of the auxiliary equipment needed for an amplifier employing parametric diodes or masers, the over-all power consumed by these systems is over a million times as much as would be required by the tunnel diode stage. Even after one has added in the power required by subsequent stages in a receiver, which would be common to any system, the simplicity of the tunnel diode may prove to be such an advantage that it will find use in airborne or satellite communications equipment despite its slightly noisier performance.

There are four demonstrations for you to see which relate to this field: an FM receiver, to demonstrate radio reception; a small FM transmitter, to demonstrate radio transmission; a microwave oscillator to demonstrate the high-frequency potential, and a crystal controlled oscillator which can operate equally well in a high temperature oven or immersed in liquid air.

The FM receiver circuit is interesting in that it shows how the tunnel diode's characteristics can be exploited -- through novel circuit design -- to produce a variety of functions from one diode that would require a large number of conventional components to duplicate. The important idea here is that the tunnel diode is a new and different component with a unique combination of electrical properties. It happens that these characteristics make it the proverbial square peg for quite a number of square holes. Tunnel diodes will also find application as local oscillators for superheterodyne receivers, as amplifying mixers and detectors, and in low-noise preamplifiers for high-frequency receivers.

Longevity:

Esaki diodes are notable for their longevity; devices made in the 1960s still function. Writing in *Nature*, Esaki and coauthors state that semiconductor devices in general are extremely stable, and suggest that their shelf life should be "infinite" if kept at room temperature. They go on to report that a small-scale test of 50-year-old devices revealed a "gratifying confirmation of the diode's longevity".[7]

References

1- Berlin, Leslie (2005). *The Man Behind the Microchip: Robert Noyce and the Invention of Silicon Valley*. Oxford University Press. ISBN 0195163435.

2- http://www.sony.co.jp/Products/SC-HP/outline/overview/history.html.

3- *Tunnel diodes, the transistor killers*, EE Times, retrieved 2 October 2009

4- Fink, pp. 7–35

5- Fink, pp. 13–64

6- L.W. Turner,(ed), Electronics Engineer's Reference Book, 4th ed. Newnes-Butterworth, London 1976 ISBN 0 408 00168 pp. 8-18

7- Esaki, Leo; Arakawa, Yasuhiko; Kitamura, Masatoshi (2010). "Esaki diode is still a radio star, half a century on". *Nature* **464** (7285): 31. doi:10.1038/464031b. PMID 20203587.