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Diode that works using quantum tunnelingTunnel diode1N3716 tunnel diode (with 0.1" jumper for scale)Component typeActiveWorking principleQuantum tunnelingInventorLeo EsakiYuriko Kurose[1]Invention year1957First produced1957First produced bySonyPin namesAnode and cathodeElectronic symbol10mA germanium tunnel diode mounted in test fixture of Tektronix571 curve tracerA tunnel diode or Esaki diode is a type of semiconductor diode that has effectively "negative resistance" due to the quantum mechanical effect called tunneling. It was invented in August1957 by Leo Esaki and Yuriko Kurose when working at Tokyo Tsushin Kogyo, now known as Sony.[1][2][3][4] In 1973, Esaki received the Nobel Prize in Physics for experimental demonstration of the electron tunneling effect in semiconductors.[5] Robert Noyce independently devised the idea of a tunnel diode while working for William Shockley, but was discouraged from pursuing it.[6] Tunnel diodes were first manufactured by Sony in 1957,[7] followed by General Electric and other companies from about 1960, and are still made in low volume today.[8]Tunnel diodes have a heavily doped positive-to-negative (P-N) junction that is about 10nm (100) wide. The heavy doping results in a broken band gap, where conduction band electron states on the N-side are more or less aligned with valence band hole states on the P-side. They are usually made from germanium, but can also be made of gallium arsenide, gallium antimonide (GaSb) and silicon materials.The negative differential resistance in part of their operating range allows them to function as oscillators and amplifiers, and in switching circuits using hysteresis. They are also used as frequency converters and detectors.[9]:735 Their low capacitance allows them to function at microwave frequencies, far above the range of ordinary diodes and transistors.812GHz tunnel diode amplifier, circa 1970Due to their low output power, tunnel diodes are not widely used: Their radio frequency output is limited to a few hundred milliwatts due to their small voltage swing. In recent years, however, new devices that use the tunneling mechanism have been developed. The resonant-tunneling diode (RTD) has achieved some of the highest frequencies of any solid-state oscillator.[10]Another type of tunnel diode is a metal-insulator-insulator-metal (MIIM) diode, where an additional insulator layer allows "step tunneling" for more precise control of the diode.[11] There is also a metal-insulator-metal (MIM) diode, but due to inherent sensitivities, its present application appears to be limited to research environments.[12]Under normal forward bias operation, as voltage begins to increase, electrons at first tunnel through the very narrow P-N junction barrier and fill electron states in the conduction band on the N-side which become aligned with empty valence band hole states on the P-side of the P-N junction. As voltage increases further, these states become increasingly misaligned, and the current drops. This is called negative differential resistance because current decreases with increasing voltage. As voltage increases beyond a fixed transition point, 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 PN junction barrier. The most important operating region for a tunnel diode is the "negative resistance" region. Its graph is different from normal P-N junction diode.Main article: Backward diodeI vs. V curve similar to a tunnel diode characteristic curve. It has "negative" differential resistance in the shaded voltage region, between V1 and V2.When used in the reverse direction, tunnel diodes are called back diodes (or backward 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 P-N junction barrier in reverse direction.I vs. V curve of 10mA germanium tunnel diode, taken on a Tektronix model571 curve tracer.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" at which point conduction begins (often accompanied by destruction of the device). In the tunnel diode, the dopant concentrations in the P and N layers are increased to a level such that the reverse breakdown voltage becomes zero and the diode conducts in the reverse direction. However, when forward-biased, an effect occurs called quantum mechanical tunneling which gives rise to a region in its voltage vs. current behavior 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 (vacuum tube).The tunnel diode showed great promise as an oscillator and high-frequency threshold (trigger) device since it operated at frequencies far greater than the tetrode could: well into the microwave bands. Applications of 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. In 1977, the IntelsatV satellite receiver used a microstrip tunnel diode amplifier (TDA) front-end in the 1415.5GHz frequency band. Such amplifiers were considered state-of-the-art, with better performance at high frequencies than any transistor-based front end.[13] The tunnel diode can also be used as a low-noise microwave amplifier.[9]:1364 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.[14] The Gunn diode has similar high frequency capability and can handle more power.Tunnel diodes are also more resistant to ionizing radiation than other diodes.[citation needed] This makes them well suited to higher radiation environments such as those found in space.Tunnel diodes are susceptible to damage by overheating, and thus special care is needed when soldering them.Tunnel diodes are notable for their longevity, with devices made in the 1960s still functioning. 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 50year-old devices revealed a "gratifying confirmation of the diode's longevity". As noticed on some samples of Esaki diodes, the gold-plated iron pins can in fact corrode and short out to the case. This can usually be diagnosed and treated with simple peroxide / vinegar technique normally used for repairing phone PCBs and the diode inside normally still works.[15]Surplus Russian components are also reliable and often can be purchased for a few pence, despite original cost being in the 3050 range. The units typically sold are GaAs based and have a Ipk/Iv ratio of 5:1 at around 120mA Ipk, and so should be protected against overcurrent.[16]Avalanche diodeGunn diodeIMPATT diodeLambda diodeResonant-tunneling diodeTunnel junctionZener diode^ a b US 3033714, issued 1962-05-08^ Esaki, Leo (15 January 1958). "New Phenomenon in Narrow Germanium p-n Junctions". Physical Review. 109 (2): 603604. Bibcode:1958PhRv..109..603E. doi:10.1103/PhysRev.109.603.^ Esaki, Reona (Leo); Kurose, Yuriko; Suzuki, Takashi (1957). Internal Field Emission at Ge P-N Junction. Physical Society of Japan 1957 annual meeting. doi:10.11316/jpsgaiyou.12.5.0_85. Retrieved 2024-07-07.^ "The Esaki Diode, Chapter 9 The Model 2T7 Transistor, Part I, Sony History". Sony Corporation. 1996. Retrieved 2018-04-04. In the first public report of the discovery (presentation at the 12th annual meeting of the Physical Society of Japan in October 1957), Takashi Suzuki, who was a student at Tokyo University of Science and doing his internship at Tokyo Tsushin Kogyo under Esaki's supervision, was a co-author. Suzuki, along with Yuriko Kurose, first observed the negative differential resistance when they were testing heavily doped P-N junctions.^ "The Nobel Prize in Physics 1973: Award ceremony speech". NobelPrize.org. Retrieved 2023-12-17.^ Berlin, Leslie (2005). The Man Behind the Microchip: Robert Noyce and the Invention of Silicon Valley. Oxford, UK: Oxford University Press. ISBN0-19-516343-5.^ (in Japanese). Archived from the original on 2 February 2009.^ Rostky, George. 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COMSAT Technical Review. 8: 487507. Bibcode:1978COMTR...8..487M. ISSN0095-9669.^ Turner, L.W., ed. (1976). Electronics Engineer's Reference Book (4thed.). London, UK: Newnes-Butterworth. pp.818. ISBN0-408-00168-2.^ Esaki, Leo; Arakawa, Yasuhiko; Kitamura, Masatoshi (2010). "Esaki diode is still a radio star, half a century on". Nature. 464 (7285): 31. Bibcode:2010Natur.464Q..31E. doi:10.1038/464031b. PMID20203587.^ "Russian tunnel diodes". TekWiki. Retrieved 13 November 2023.Wikimedia Commons has media related to Tunnel diodes."Tunnel Diode tutorial".Retrieved from " Learn how tunnel diodes work and their unique negative resistance characteristic. Discover the applications of tunnel diodes in high-speed electronics, microwave communication, temperature sensing, and electronic noise generation. Tunnel diodes, also known as Esaki diodes after their inventor, Leo Esaki, are a special type of diode that have a unique characteristic known as negative resistance. This means that the current flowing through the diode decreases as the voltage across it increases. This may seem counterintuitive, but it is precisely this property that makes tunnel diodes useful in a variety of applications, from high-speed electronics to microwave communication.The Basics of TunnelingIn order to understand how tunnel diodes work, it is necessary to first understand the concept of tunneling. Tunneling is a quantum mechanical phenomenon that allows particles to pass through energy barriers that would normally be impassable according to classical physics. This occurs because the wave function of a particle extends beyond its physical boundaries, allowing it to tunnel through the barrier.In the case of a tunnel diode, the energy barrier is created by a narrow depletion region that separates two heavily doped regions of semiconductor material. When a voltage is applied across the diode, the depletion region becomes narrower, allowing electrons to tunnel through the barrier and flow from one region to the other.Negative Resistance Tunnel diodes utilize the fact that as the voltage across the diode increases, the current flowing through it actually decreases. This is because as the voltage increases, the depletion region becomes wider, which in turn reduces the number of electrons that are able to tunnel through the barrier. This results in a decrease in current, despite the increase in voltage.This negative resistance behavior is exploited in a number of applications, such as in high-speed switching circuits, where tunnel diodes can switch on and off much faster than traditional diodes. They are also used in microwave applications, where their negative resistance can be used to amplify signals.Despite their unique properties, tunnel diodes have largely been replaced by other types of diodes in most applications. However, they continue to be used in specialized applications where their negative resistance behavior is required.Applications of Tunnel DiodesTunnel diodes find a wide range of applications due to their unique characteristics. Here are some of the most important applications of tunnel diodes:High-Speed ElectronicsTunnel diodes are used in high-speed electronics, where their negative resistance allows for faster switching speeds. They are used in pulse generators, digital logic circuits, and high-frequency oscillators. In these applications, tunnel diodes allow for faster switching speeds than traditional diodes.Microwave CommunicationTunnel diodes find extensive use in microwave communication. They are used in microwave oscillators, amplifiers, and detectors. In these applications, tunnel diodes are used for their high-frequency performance and low noise properties. Due to their negative resistance, they can be used to amplify signals and also for frequency mixing.Temperature SensingTunnel diodes are used in temperature sensing applications due to their sensitivity to temperature changes. They are used in temperature sensors that can measure temperatures up to 1000C. In these applications, the voltage across the diode changes with temperature, allowing for temperature measurement.Electronic Noise GenerationTunnel diodes can be used to generate electronic noise. They are used in electronic test equipment to generate random noise signals for testing purposes. In these applications, tunnel diodes are used because of their fast switching speeds and high-frequency range.ConclusionIn conclusion, tunnel diodes are a unique type of diode that have a negative resistance characteristic, which allows for faster switching speeds and high-frequency performance. They are used in a wide range of applications, from high-speed electronics to microwave communication, temperature sensing and electronic noise generation. While they have been largely replaced by other types of diodes in most applications, they continue to find use in specialized applications where their negative resistance behavior is required. Definition: A heavily doped two-terminal semiconductor device through which electric current flows because of tunneling (or tunnelling) of electrons is known as Tunnel Diode. It possesses the negative resistance characteristic in which current decreases even when the applied voltage is increased.Tunneling basically denotes the penetration of electrons through a high barrier. As highly doped diode has a thin depletion region. It works on the principle of Quantum mechanical tunneling. As a tunnel diode shows fast switching characteristics thus it finds extensive applications in the field of the microwave. Content: Tunnel Diode Symbol of Tunnel diodeThe symbolic representation of tunnel diode is shown below:Construction of Tunnel DiodeThe basic manufacturing material of a tunnel diode is germanium, gallium arsenide or gallium antimonide. It is not formed using silicon as its basic material. This is so because the ratio of maximal value of forward current to valley current in case of silicon is very less. However, gallium arsenide has the maximal value of this ratio thus is widely used.The structural representation of tunnel diode is shown below:In the tunnel diode, the doping concentration is very high. The concentration of doped impurity in a tunnel diode is thousand times more as compared to any normal diode. This is done so as to have thin depletion region, that is the basis of tunneling effect.This diode was invented by Dr Leo Esaki in 1957. Hence it is also known as Esaki Diode.Working principle of Tunnel DiodeAs we have already discussed that the doping concentration in tunnel diode is very high. Due to this, so, the reduced width of the depletion region causes the penetration of charge carriers across the junction even when the carriers do not have enough energy to jump across it.Let us understand the working of a tunnel diode by considering some conditions.In a zero biased condition, the highly doped diode is not provided with any input voltage. So, in no biased condition, an overlapping is noticed between the conduction band of n region and valence band of p region.This overlapping causes the two bands to appear at the almost same energy level. As the depletion width is very small thus, without any applied potential, due to temperature variation, electrons from n side tunnels to p side.Similarly, holes from p side tunnels to n side.As the tunneling is equal for both the carriers thus no current is noticed in case of zero biased condition.Now, when a certain voltage is applied. Such that forward voltage is less than the barrier potential of the depletion region.But, still, a small current flows through the diode. This is so, because, the electrons in the conduction band of n region will penetrate over thin depletion region and reaches valence band of p region.The velocity of punching of these electrons is somewhat similar to the velocity of light. Hence, this punching generates a forward current through the device.Now, when the applied forward voltage is increased further. So, in this case, a large current starts to flow through the device. The electrons that have sufficient energy moves across the junction. But those which has less energy will also penetrate the junction due to thin depletion width.In the tunnel diode, electrons tunnel through the junction to reach p region. This is so because now, the conduction band of n region is parallel with the valence band of p region. Thus, the highest (peak) current is achieved in this case.If the forward potential applied to the device is increased further. In this case the conduction band and valence band shows some overlapping. This causes a small current to flow through the device. However, here with the increased potential, the current through the device now starts decreasing. After this, the applied potential is increased further. But now applying the voltage will cause the current through the device to reach nearly zero. As the conduction band and valence band are no longer overlapping. Then, the conduction band and valence band are no longer forming an overlap connection. But, the applied potential will now overcome the barrier potential of the depletion region. So, current as in case of the normal diode will flow through the tunnel diode also.This is how a tunnel diode works.Characteristics of Tunnel DiodeThe figure below represents the VI characteristics of a tunnel diode: Here we can see the origin of the graph shows the zero biased condition of the tunnel diode. Where no input voltage is provided and so no current is noticed in the device. As the input voltage is increased, the current is noticed to flow through the device. This current increases with the increase in the voltage applied and a peak of forward current is reached. This is clearly represented by point A in the above figure.As we discussed already that after reaching the maximum value, the current now starts decreasing. This starts at point B and its value is reduced further to reach the valley point. This is the region of the characteristic where the decrement of the current with the increase in the voltage applied is noticed and this current is the negative resistance region. After this region valley point is achieved which shows the decrement of the current nearly up to zero at point B. But as the potential has increased the device now starts behaving as normal diode. The current, begins to increase from this particular point.Advantages of Tunnel DiodeIt is a low power consuming device.It is not expensive.A tunnel diode is easy to operate and provides high-speed operation. Disadvantages of Tunnel DiodeThe abrupt change in load current with the applied voltage is sometimes treated as its drawback.Proper isolation between input and output is not maintained as it is a two terminal device.Applications of Tunnel DiodeIt is widely used in microwave and high-frequency applications because of its fast response. It can also be used as amplifiers and in oscillator circuits. Tunneling current: It is the current flowing through the device due to the punching of electrons across the junction. The thin depletion width allows some free electrons to tunnel through the junction rather than jumping over it. This penetration of electrons generates a current known as Tunneling current.Negative resistance characteristics: The negative resistance characteristic is the special ability of tunnel diode in which current represents fall when the voltage provided to it rises.Valley current: When tunneling reaches its minimum value with the increase in the forward potential. Then the lowest value of tunneling current is the valley point of the device.So, we can conclude that the diode possesses conduction initially due to quantum mechanics. After reaching some specified large forward potential the tunnel diode begins to behave like a normal diode. The tunnel diode is also known as the "Esaki diode". It was invented by "Leo Esaki" in 1957, and for this invention, he received Nobel in 1973. It exhibits negative resistance, negative resistance means current decreases when voltage increases.What is a Tunnel Diode?A tunnel diode is a very heavily doped p-n junction diode. In a Tunnel diode electric current decreases as the applied voltage increases, and at high voltage, it works as an ordinary p-n junction diode. In the Tunnel diode, electric current is due to the "Tunneling effect". Due to its fast switching ability, it is used in high-frequency oscillators and amplifiers. Due to the tunneling effect, charge carriers moves across the depletion layer at very low voltage. The circuit shown below is the symbolic diagram of the Tunnel diode. In the tunnel diode the p-terminal acts as an anode and the n-terminal acts as a cathode.Tunnel Diode SymbolWorking of Tunnel DiodeThe width of the depletion region depends on the level of doping in semiconductor material. If the doping level is high then the width of the depletion region is low and if the doping level is low then the width of the depletion region is very thinbecause the doping level is very high.A tunnel diode is very highly doped semiconductor device, which is why tunnel diode is doped semiconductor device, through which electric current flows in the forward bias, which moves across the depletion region from n-type semiconductor towards p-type semiconductor.1. Unbiased condition or Unbiased Tunnel DiodeAn unbiased condition means when no voltage is applied to the tunnel diode, the conduction band of n-type is overlapped with the p-type semiconductor material, due to heavy doping.Because of overlapping of the conduction band of n-type and the hole of valence band of p-type are nearly at the same level. thus when temperature increase some electron tunnel from conduction band of n-type to valence band of p-type and some hole tunnel from valence band of p-type to conduction band n-type semiconductor material, but the current flow is zero because of the number of tunneled electron and holes are same but in opposite direction.2. In Forward Biased Condition (Some positive voltage is applied across tunnel diode)When a small positive voltage is applied less than the potential of the depletion layer, then no electrons from the n-region tunnel through the p-region.In this condition some of the electrons of conduction band of n-type is overlapping with the valence band of p-type, this creates a small current flow through the diode. 3. At Vp (voltage is increase slowly)When voltage is increased a large number of free electron at n-side and holes at p-side generates. Because of the increase in voltage the over lapping is increased. Energy level of conduction band of n-type is exactly equal to the energy level of the empty valence band of p-type, this gives maximum tunnel current.4. If the applied voltage is more than peak voltage(V>Vp)When we further increase the voltage more than the peak voltage, the energy level of conduction band at n-side and the valence band at p-side misalign. Due to this misalignment tunneling of charge carrier decreases, as result decrease in tunnel current.If the applied voltage is increased largely then the tunnel diode behaves like an ordinary diode, and show zero tunnel current and maximum diode current.If the applied voltage is greater than the voltage of the depletion layer the tunnel current start decreasing till the valley voltage level after that current increase exponentially.Operating Region of Tunnel DiodeOhmic region:- Portion of the curve in which current increases linearly is known as ohmic region. In ohmic region tunnel diode behaves like linear diode. Biasing voltage of ohmic region is zero to peak voltage.Negative resistance region:- Portion of the curve in which tunnel current decreases known as negative resistance region. Biasing voltage is from peak voltage to the valley voltage. Negative resistance region is widely used characteristic of tunnel diode. Saturation region:- At very high voltage diode attained saturation level in saturation region tunnel diode behaves like ordinary diode in which current increases exponentially.Types of Tunnel DiodesThere are different types of tunnel diode based on their structure and application in their development.1. Single-Well Tunnel Diode: This type of diode exhibits negative differential resistance and is used in amplifiers and oscillator circuits.2. Double-Barrier Tunnel Diode: This diode is used in applications such as millimeter wave oscillators because it operate at higher frequencies.3. Superlattice Tunnel Diode: This is used for more precise control over the tunneling process and can lead to improved performance characteristics.4. Resonant Tunnel Diode5. Esaki Inter-band Tunnel Diode: Esaki inter-band tunnel diode is an extension of the traditional tunnel diode it is used for higher-frequency applications.Advantage of Tunnel DiodeVery small size.Easy to fabricate.Low cost.Low power consumption.Low noise.High speed.Disadvantage of Tunnel DiodeNo proper DC isolation.Smaller voltage swing.It can not be fabricated in large amount.Applications of Tunnel DiodeTunnel diode have fast switching characteristics so it is used in microwave application.Tunnel diode is used in relaxation oscillator circuit.Used as logic memory storage devices.Used in FM receivers. A tunnel diode, also known as an Esaki diode, is a type of semiconductor diode that exhibits negative resistance due to the quantum mechanical phenomenon called tunneling. Tunnel diodes have a pn junction that is heavily doped and has a depletion region of approximately 10 nm wide. This extreme doping results in a broken bandgap, where conduction band electron states on the N-side align with valence band hole states on the P-side. Due to transit time and other effects, transistors are limited in their application in high-frequency ranges. However, many devices utilize semiconductors negative conductance properties for such applications. One such device is the tunnel diode, also known as the Esaki diode, named after L. Esaki for his work on this effect. The dopant concentration in the p and n regions is extremely high, ranging from 1024 to 1025 m-3. The pn junction is abrupt, resulting in a narrow depletion region. When a forward bias is applied, the current-voltage characteristics of a tunnel diode exhibit a negative slope region. The term tunnel diode refers to a phenomenon within the diode due to quantum mechanical tunneling. The diode is heavily doped, so at a temperature of absolute zero, the Fermi levels lie within the bias of the semiconductors. When a forward bias is applied to a p-n junction, the Fermi level on the p-side becomes higher than that of the n-side. This leads to the tunneling of electrons from the balance band of the p-side to the conduction band of the n-side. As the reverse bias strength increases, the tunnel current also increases. When a forward bias is applied, the Fermi level of the n-side becomes higher than that of the p-side. This causes the tunneling of electrons from the n-side to the p-side. The amount of current generated by tunneling is much larger than the normal diode current. As the forward bias increases, the tunnel current also increases to a certain limit. When the band edge of the n-side is aligned with the Fermi level in the p-side, the tunnel current reaches its maximum. The tunnel current decreases as the forward bias increases, and the desired negative conduction region is achieved. It further increases the forward bias, resulting in a normal pn junction current exponentially proportional to the applied voltage. These features can describe the V-I characteristics of the tunnel diode. The negative resistance is commonly utilized to generate oscillation. The symbol for a tunnel diode is depicted below. In an unbiased tunnel diode, no external voltage is applied. Due to heavy doping, the conduction band of the n-type semiconductor overlaps with the valence band of the p-type material. As a result, electrons in the n-region and holes in the p-region are at the same energy level and overlap. At higher temperatures, some electrons from the conduction band of the n-region tunnel into the valence band of the p-region, and holes move in the opposite direction. Since an equal number of electrons and holes move in opposite directions, the net current remains zero. The probability (P) of a particle crossing the barrier is given by: Where: P = Probability of tunneling W= Barrier width E = Barrier energy When a small voltage is applied to the tunnel diode, which is less than the built-in potential of the depletion layer, there is no significant forward current through the junction. However, a small number of electrons from the n-regions conduction band start tunneling into the p-regions valence band. This movement results in a small forward-biased tunnel current. As voltage increases, slightly, tunnel current starts flowing through the diode. With an increase in the applied voltage, more free electrons are generated in the n-region, and more holes appear in the p-region. The overlap between the conduction and valence bands increases, enabling more electrons to tunnel through the barrier. The maximum tunneling current occurs when the energy levels of the n-side conduction band and the p-side valence band are aligned. At this point, the peak current flows through the tunnel diode. If the applied voltage continues to increase, the conduction and valence bands slightly misalign, reducing the tunneling probability. However, some overlap still exists, and electrons continue to move from the n-regions conduction band to the p-regions valence band. At this stage, the tunnel current starts decreasing, leading to the negative resistance region of the tunnel diode. When the applied voltage is increased beyond a certain level, the conduction band and valence bands no longer overlap, preventing electron tunneling. At this stage, the tunneling current drops to zero, and the tunnel diode functions like a standard PN junction diode. If the applied voltage exceeds the built-in potential of the depletion layer, regular forward current starts flowing through the diode. In this condition, as voltage increases, the current initially decreases, leading to a negative resistance region. Tunnel diodes operating in this negative resistance region are widely used in applications such as amplifiers and oscillators due to their unique high-speed switching properties. A tunnel diode is a semiconductor diode capable of operating at very high speeds, particularly in the microwave frequency. It derives its unique characteristics from a quantum mechanical effect known as tunneling. Thanks to its negative slope characteristics, it is ideal for use in fast oscillators and receivers. However, its applications are somewhat limited due to its inability to be used in large integrated circuits. When a voltage is applied, a current begins to flow through it. As the voltage increases, the current also increases. However, once the voltage reaches a certain point, the current suddenly increases again and the tunnel diode behaves like a normal diode. This unique behavior makes it useful for various special applications, which we will explore below. Oscillator Circuits: Tunnel diodes are often utilized as high-frequency oscillators due to their rapid transition between high electrical conductivity states. These diodes can generate oscillations as high as 5 GHz; they can even produce oscillations up to 100 GHz in digital circuits. Used in Microwave Circuits: Ordinary diode transistors are not suitable for efficient performance in microwave operations. To overcome this limitation, tunnel diodes are utilized in microwave generators and amplifiers. These diodes were previously popularly used in microwave waves and satellite communication equipment. However, in recent times, their usage has declined considerably due to the availability of transistors that operate in this frequency range. Resistant to Nuclear Radiation: Tunnel diodes have remarkable resistance to magnetic fields, high temperatures, and radioactivity. This makes them an ideal component for modern military equipment. Additionally, they are used in nuclear magnetic resource machines. However, the most significant application of tunnel diodes is in satellite communication equipment. Share copy and redistribute the material in any medium or format for any purpose, even commercially. Adapt remix, transform, and build upon the material for any purpose, even commercially. The licensor cannot revoke these freedoms as long as you follow the license terms. Attribution You must give appropriate credit , provide a link to the license, and indicate if changes were made . You may do so in any reasonable manner, but not in any way that suggests the licensor endorses you or your use. ShareAlike If you remix, transform, or build upon the material, you must distribute your contributions under the same license as the original. No additional restrictions You may not apply legal terms or technological measures that legally restrict others from doing anything the license permits. You do not have to comply with the license for elements of the material in the public domain or where your use is permitted by an applicable exception or limitation . No warranties are given. The license may not give you all of the permissions necessary for your intended use. For example, other rights such as publicity, privacy, or moral rights may limit how you use the material. A diode is the most fundamental component used in electronic circuits. However, there are different types of diodes being used each designed for its specific applications. One such for we are going to discuss here in this article is Tunnel Diode.A Japanese physicist Leo Esaki in 1957 invented a new type of diode by increasing the doping concentration of a PN junction diode. In doing so, he observed Negative Resistance due to the Quantum mechanical effect which he named the Electron Tunneling effect. He was awarded the Nobel prize for discovering the electron tunneling effect. Therefore the Diode was named Tunnel Diode or Esaki Diode. It has negative resistance which means the current decreases with an increase in voltage in its operating range. It has the capability of high-speed switching thus it is used in high-frequency applications. What is Tunnel Diode?A Tunnel diode also known as Esaki diode is a type of diode made from the PN junction of a heavily doped semiconductor whose current decrease with an increase in voltage due to negative resistance. This phenomenon is also called electron tunneling. It enables high-speed switching that makes it suitable for high-frequency applications such as in computers. The Tunnel diode can be represented using two different symbols add shown in the figure below.It had two terminals named anode and cathode. The anode is the P-region while the cathode is the N-region. The anode is positively charged with holes in the majority and it attracts electrons from the cathode. While the cathode is negatively charged with the majority of electrons and attracts holes from the anode.Related Post:Different Types of Diodes SymbolsConstructionDuring the construction of the Tunnel diode, the following two factors are really important.Material (peak current to valley current ratio)Doping ConcentrationMaterial plays a vital role in the performance of the tunnel diode. When a forward voltage is applied, the current increases up to peak current as in any other normal diode. With a further increase in the forward voltage, the current starts decreasing down to the minimum point called the valley point. The ratio of peak current to valley current must be large to enable electron tunneling. Silicon has a very small ratio of peak current to valley current compared to germanium. Therefore, silicon is not suitable for tunnel diodes. Materials such as germanium, gallium arsenide, and gallium antimonide are used for the construction of Tunnel diodeThe semiconductor used for tunnel diode must have a very high doping concentration. Semiconductors are naturally neutral i.e. the number of electrons and holes are equal. Impurities are added to increase the number of electrons or holes to form either n-type or p-type semiconductors. The doping level is almost 1000 times greater than any normal diode. The heavy doping reduces the width of the depletion region. This also reduces the reverse breakdown voltage of the diode.Here is the structure of the Tunnel diode given below. As far as the construction of a Tunnel diode is concerned, it is very simple to fabricate. The whole structure is hermetically sealed with a ceramic body. A very small tin dot of 50 m in diameter is alloyed to a square pallet of 0.5 mm that is made of heavily doped n-type Ga, GaAs, or GaSb. The pallet is then soldered on top of the anode. The anode also helps in heat dissipation. The tin dot is connected to the cathode through a mesh screen that helps in the reduction of inductance.Electron TunnelingElectron tunneling of quantum tunneling is a quantum effect where charge carriers or electrons easily move through a junction due to its very small depletion region. An electron must acquire a certain potential higher than the in-built potential of the barrier to pass through it. Since the depletion region in the tunnel diode is largely reduced in nanometers thanks to heavy doping concentration, the electrons can punch through the junction even if the voltage is lower than the barrier potential. This effect is called electron tunneling & the diode is called the tunnel diode.We can compare a conventional diode with a tunnel diode using the given figure. The combination of p & n semiconductors forms a junction called the barrier or depletion region. It is made of an equal number of+ve & -ve ions. Therefore it has no majority carriers. Due to the combination of P & N semiconductors, a potential is formed across the barrier called the barrier potential. The electron must acquire energy greater than the barrier potential to pass through it. However, quantum mechanics say that if the depletion width becomes very small the electrons can penetrate through the barrier having lower energy. The barrier potential is directly proportional to the junction width. The tunnel diode has a very small barrier width in nanometers as compared to a normal PN diode.Therefore the electrons in a normal diode require applied voltage greater than the barrier potential to pass through. While tunnel diode can conduct a large current at a small applied voltage lower than the barrier potential due to electron tunneling from the conduction band of the n-region into the valance band of the p-region. Electron Tunneling can be clarified using the given energy bands. In a tunnel diode, The conduction band and valance band energy level of an n-type semiconductor is lower than the energy level of conduction and valance band of a p-type semiconductor. Therefore the conduction band of n-type (that carries electrons) & the valance band of p-type (holes) fall at the same energy level. So the electrons from the conduction band of the n-region pass through the narrow junction into the valence band of the p-region.Due to electron tunneling, the tunnel can conduct a large current at a small forward voltageRelated Posts:Types of Diodes and Their Applications 24 Types of DiodesWorking of Tunnel DiodeThe working of the Tunnel diode is explained in each separate condition.Unbiased ConditionIn unbiased conditions, there is no voltage applied to the tunnel diode. In unbiased conditions, the conduction band of a p-type semiconductor overlaps the valance band of an n-type semiconductor due to heavy doping. Therefore the electrons from the n-region fall nearly at the same energy level as the holes from the p-region. Due to similar energy levels & increase in temperature, the electrons from the n-region tunnel into the p-region. While the holes from the p-region tunnel into the n-region.However, there is no current flow through the tunnel diode in unbiased conditions because the net current is zero due to the tunneling of the number of electrons and holes are equal.ForwardBiasedIn forward biased condition, the p-side is connected to the positive terminal and the n-side is connected to the negative terminal of the battery. The output characteristics of the Tunnel diode vary with an increase in applied forward voltage. Initially, it acts as a normal diode whose current increase with an increase in voltage. After a certain voltage level, the current starts decreasing known as the negative resistance. Each level of the stage is explained below. Small voltage appliedWhen a small forward voltage whose magnitude is less than the built-in barrier potential is applied to the tunnel diode, no electron is passed through the depletion region & no forward current is generated due to it. The small applied potential reduces the energy band gap between the electrons & holes and they start to overlap with each other as shown in the figure. The energy level of the electrons in the conduction band & holes in the valance band becomes slightly similar.Due to the overlapping of energy bands & the thin depletion region, a small number of electrons tunnel through the depletion region using the tunneling effect. This electron tunneling causes a small forward current through the diode.Applied Voltage Slightly IncreasedWhen the applied voltage is increased, the electrons are energized and the energy band gap reduces even further. In fact, the energy level of the electrons in the conduction band and the holes in the valance band become parallel i.e. both are at the same level as shown in the figure. Therefore, the electrons can easily pass through the depletion region into the p-region. In such conditions, the forward current reaches its highest peak. This large forward current is the product of two factors; flow of energized electrons & flow of electrons due to the thin depletion region.Applied Voltage Further IncreasedWhen the applied voltage is further increased, the conduction band and the valence band start to misalign and the energy band gap starts to increase. Due to this misalignment, the forward current starts to decrease down to the minimum point called the valley point. This is called negative resistance & the tunnel diode is designed to operate in this region.Increasing the voltage further completely diminishes the overlapping between the conduction band of the n-region and the valence band of the p-region. In this condition, there is no tunnel current as the energy band gap is huge. However, there is a large forward current due to the high potential applied between the thin depletion region. Therefore, the diode starts to operate as a normal PN Junction diode.Related Posts: In the reverse bias condition, the p-side is connected to the negative terminal & the n-side is connected to the positive terminal of the battery. In such conditions, the tunnel diode operates as a back or backward diode. Since it has a very thin virtually no depletion region due to the heavy doping concentration, it can conduct a large amount of reverse current. It remains in a state of conduction in reverse bias as in backward diode.Due to heavy doping concentration, the peak inverse voltage PIV is small as compared to the maximum forward voltage.Equivalent Circuit of Tunnel DiodeA Tunnel Diode can be represented by an equivalent circuit using a resistor, inductor & capacitor as shown below. The main feature of the Tunnel diode is the negative resistance region & the diode resistance in this region is represented by -Ro. The Co represents the capacitance of the junction. The Ls is the series inductance due to the leads of the diode & Rs is the series equivalent resistance.Related Posts: Photodiode: Types, Construction, Operation, Modes, Performance & ApplicationsVI Characteristics of Tunnel DiodeThe VI Characteristics show the relationship between the applied voltage and the diode current as shown below. The applied voltage V is represented by the x-axis and the diode current I is represented by the y-axis. The graph shows the operation in both forward and reverse bias In forward bias, initially, there is no forward current at zero voltage. However, with the increase in voltage, the diode immediately starts conduction & the forward current increases up to the peak current Ip, at this point the voltage is Vp. With a further increase in voltage above Vp, the forward current decreases down to the minimum value Iv called valley point & this minimum current is called valley current. This region is called the negative resistance region. The Tunnel diode does not consume power but rather produces it in this region & it mainly operates in this region.Beyond the valley point, the diode operates like any conventional diode. The forward current increase with an increase in voltage.In reverse bias, the diode conducts a large reverse current due to heavy doping concentration. It has a very small almost zero depletion width. It operates like an excellent conductor in reverse bias. It is only operated in forward bias.Related Posts: Advantages & Disadvantagesof Tunnel DiodeAdvantages of Tunnel DiodeHere are some of the advantages of Tunnel diodeA tunnel diode has negative resistance that is useful in oscillators and amplifiers.It operates at a very high switching speedIt is suitable for high frequencyIt is easy to operate.It has low power dissipation and is energy efficient.It has a high disability with a longer life span.It operates very smoothly with low noise and it is also immune to noise interference.It has a simple design to fabricate and is low cost.It is inexpensive.Disadvantages of Tunnel DiodeHere are some disadvantages of the Tunnel diode.It does not provide isolation between its input and output as it has only two terminals.It has low power ratings & cannot handle high current & temperature.Its output voltage swingsIt has a relatively higher manufacturing cost.Related Posts: Applications of Tunnel DiodeA tunnel diode is mainly used for its fast switching speed & negative resistance. It has limited application due to its low power ratings. Here are some applications of the Tunnel diode.OscillatorA tunnel diode due to its high switching speed is best for high-frequency oscillators. It forms a very stable oscillator however it cannot operate at low frequency. A practical circuit diagram of the tunnel diode oscillator is given below.The two resistor R1 & R2 is used for biasing where R1 is used to set proper biasing for current while R2 sets biasing current for the tank circuit. The tank circuit is composed of inductor L & capacitor C and a resistance Rp in parallel. The tank circuit resonates at a selected frequency. The diode having negative resistance Rn (in the negative resistance region) is connected in parallel with the tank circuit. The equivalent resistance Req of such parallel resistance (Req & Rn) is given byReq = RpRn/Rp-RnAccording to the given equation, the Req depends on the value of the negative resistance Rn & Rp. If the Rp is higher than Rn, the equivalent resistance is negative & the oscillation amplitude rises above the negative resistance range of the diode. On the contrary, if the Rp is less than Rn, the equivalent resistance is positive and the oscillation amplitude decreases with time.In order to obtain maximum output, the operating point must be set at the center of the negative resistance region. The tunnel diode negative resistance region lies between 0.1v & 0.3v.Tunnel diodes can be used as high-frequency oscillators with oscillation as high as 100Ghz. However, due to their high switching speed, they are less efficient at low-frequency operation.Envelope DetectorAn envelope detector is an electronic circuit that extracts the message signal from the amplitude modulated AM signal in the demodulator. A tunnel diode being a high-speed diode can detect small variations in a high-frequency AM signal.AmplifierThe tunnel diode is used as an amplifier. Due to its low noise operation, its amplifier is used as the first stage amplifier in the receiver.Microwave CircuitMicrowave circuits require high-speed switching therefore normal diode is not suitable for operation in these circuits. In satellite communication equipment, a tunnel diode is used for microwave generation and amplifiers. With the invention of high-speed transistors, modern satellites now use a high-speed transistor.Here is a list of applications of tunnel diode:Having low power ratings, it is used in low-current high-frequency applications.Its negative resistance is used in oscillator circuits and reflection amplifiers.It is used in relaxation oscillator circuit.It is used in aerospace hardware & RADAR.It can conduct in reverse bias, therefore it is used in the frequency converter.It is used as a logic memory storage device in digital circuits because of its triple-valued characteristics.It is used in computers for its high-speed switching.It is used in a one-shot multivibrator circuit.It is used as a detector in receivers to extract the message signal from the modulated signal.It is used in solid-state circuits.Related Posts:Applications of DiodesPhotodiode: Types, Construction, Operation, Modes, Performance & ApplicationsDiode Formulas and Equations Zenner, Schockley and RectifierHow to Test a Diode using Digital and Analog Multimeter? 4 Ways.Blocking Diode and Bypass Diodes in a Solar Panel Junction BoxSimple Overvoltage Protection Circuit using Zener DiodeThyristor and Silicon Controlled Rectifier (SCR) Thyristors ApplicationsMOSFET Working, Types, Operation, Advantages, and ApplicationsIGBT? Construction, Types, Working and ApplicationsGTO? Types, Construction, Working and ApplicationsDIAC? Symbol, Construction, Working and ApplicationsTRIAC? Symbol, Construction, Working and ApplicationsDifference Between Diode and SCR (Thyristor)Difference Between Diode and TransistorDifference Between Photodiode and PhototransistorZener Diode and Zener Voltage Regulator CalculatorSimple Overvoltage Protection Circuit using Zener DiodeQuantum mechanical phenomenonPart of a series of articles aboutQuantum mechanics i d d t | = H ^ | {\displaystyle i\hbar {\frac {d}{dt}}|\Psi \rangle ={\hat {H}}|\Psi \rangle } Schrdinger equationIntroductionGlossaryHistoryBackgroundClassical mechanicsOld quantum theoryBraket notationHamiltonianInterferenceFundamentalsComplementarityDecoherenceEntanglementEnergy levelMeasurementNonlocalityQuantum numberStateSuperpositionSymmetryTunnellingUncertaintyWave functionCollapseExperimentsBell's inequalityCHSH inequalityDavissonGermerDouble-slitElitzurVaidmanFranckHertzLeggett inequalityLeggettGarg inequalityMachZehnderPopperQuantum eraserDelayed-choiceSchrdinger's catSternGerlachWheeler's delayed-choiceFormulationsOverviewHeisenbergInteractionMatrixPhase-spaceSchrdingerSum-over-histories (path integral)EquationsDiracKleinGordonPauliRydbergSchrdingerInterpretationsBayesianConsciousness causes collapseConsistent historiesCopenhagende BroglieBohmEnsembleHidden-variableMany-worldsObjective-collapseQuantum logicSuperdeterminismRelationalTransactionalAdvanced topicsRelativistic quantum mechanicsQuantum field theoryQuantum information scienceQuantum computingQuantum chaosEPR paradoxDensity matrixScattering theoryQuantum statistical mechanicsQuantum machine learningScientistsAharonovBellBetheBlackettBlochBohmBohrBornBosede BroglieComptonDiracDavissonDebyeEhrenfestEinsteinEverettFockFermiFeynmanGlauberGutzwillerHeisenbergHilbertJordanKramersLambLandauLaueMoseleyMillikanOnnesPauliPlanckRabiRamanRydbergSchrdingerSimmonsSommerfeldvon NeumannWeylWienWignerZeemanZeilingervteIn physics, quantum tunnelling, barrier penetration, or simply tunnelling is a quantum mechanical phenomenon in which an object such as an electron or atom passes through a potential energy barrier that, according to classical mechanics, should not be passable due to the object not having sufficient energy to pass or surmount the barrier.Tunneling is a consequence of the wave nature of matter, where the quantum wave function describes the state of a particle or other physical system, and wave equations such as the Schrdinger equation describe their behavior. The probability of transmission of a wave packet through a barrier decreases exponentially with the barrier height, the barrier width, and the tunneling particle's mass, so tunneling is seen most prominently in low-mass particles such as electrons or protons tunneling through microscopically narrow barriers. Tunneling is readily detectable with barriers of thickness about 13nm or smaller for electrons, and about 0.1nm or smaller for heavier particles such as protons or hydrogen atoms.[1] Some sources describe the mere penetration of a wave function into the barrier, without transmission on the other side, as a tunneling effect, such as in tunneling into the walls of a finite potential well.[2][3]Tunneling plays an essential role in physical phenomena such as nuclear fusion[4] and alpha radioactive decay of atomic nuclei. Tunneling applications include the tunnel diode,[5] quantum computing, flash memory, and the scanning tunneling microscope. Tunneling limits the minimum size of devices used in microelectronics because electrons tunnel readily through insulating layers and transistors that are thinner than about 1nm.[6]The effect was predicted in the early 20th century. Its acceptance as a general physical phenomenon came mid-century.[7]Animation showing the tunnel effect and its application to an STMQuantum tunnelling falls under the domain of quantum mechanics. To understand the phenomenon, particles attempting to travel across a potential barrier can be compared to a ball trying to roll over a hill. Quantum mechanics and classical mechanics differ in their treatment of this scenario.Classical mechanics predicts that particles that do not have enough energy to classically surmount a barrier cannot reach the other side. Thus, a ball without sufficient energy to surmount the hill would roll back down. In quantum mechanics, a particle can, with a small probability, tunnel to the other side, thus crossing the barrier. The reason for this difference comes from treating matter as having properties of waves and particles.A simulation of a wave packet incident on a potential barrier. In relative units, the barrier energy is 20, greater than the mean wave packet energy of 14. A portion of the wave packet passes through the barrier.The wave function of a physical system of particles specifies everything that can be known about the system.[8] Therefore, problems in quantum mechanics analyze the system's wave function. Using mathematical formulations, such as the Schrdinger equation, the time evolution of a known wave function can be deduced. The square of the absolute value of this wave function is directly related to the probability distribution of the particle positions, which describes the probability that the particles would be measured at those positions.As shown in the animation, when a wave packet impinges on the barrier, most of it is reflected and some is transmitted through the barrier. The wave packet becomes more de-localized: it is now on both sides of the barrier and lower in maximum amplitude, but equal in integrated square-magnitude, meaning that the probability the particle is somewhere remains unity. The wider the barrier and the higher the barrier energy, the lower the probability of tunneling.Some models of a tunneling barrier, such as the rectangular barriers shown, can be analysed and solved algebraically.[9]:96 Most problems do not have an algebraic solution, so numerical solutions are used. "Semiclassical methods" offer approximate solutions that are easier to compute, such as the WKB approximation.The Schrdinger equation was published in 1926. The first person to apply the Schrdinger equation to a problem that involved tunneling between two classically allowed regions through a potential barrier was Friedrich Hund in a series of articles published in 1927. He studied the solutions of a double-well potential and discussed molecular spectra.[10] Leonid Mandelstam and Mikhail Leontovich discovered tunneling independently and published their results in 1928.[11]In 1927, Lothar Nordheim, assisted by Ralph Fowler, published a paper that discussed thermionic emission and reflection of electrons from metals. He assumed a surface potential barrier that confines the electrons within the metal and showed that the electrons have a finite probability of tunneling through or reflecting from the surface barrier when their energies are close to the barrier energy. Classically, the electron would either transmit or reflect with 100% certainty, depending on its energy. In 1928 J. Robert Oppenheimer published two papers on field emission, i.e. the emission of electrons induced by strong electric fields. Nordheim and Fowler simplified Oppenheimer's derivation and found values for the emitted currents and work functions that agreed with experiments.[10]A great success of the tunnelling theory was the mathematical explanation for alpha decay, which was developed in 1928 by George Gamow and independently by Ronald Gurney and Edward Condon.[12][13][14][15] The latter researchers simultaneously solved the Schrdinger equation for a model nuclear potential and derived a relationship between the half-life of the particle and the energy of emission that depended directly on the mathematical probability of tunneling. All three researchers were familiar with the works on field emission,[10] and Gamow was aware of Mandelstam and Leontovich's findings.[16]In the early days of quantum theory, the term tunnel effect was not used, and the effect was instead referred to as penetration of, or leaking through, a barrier. The German term wellenmechanische Tunneleffekt was used in 1931 by Walter Schottky.[10] The English term tunnel effect entered the language in 1932 when it was used by Yakov Frenkel in his textbook.[10]In 1957 Leo Esaki demonstrated tunneling of electrons over a few nanometer wide barrier in a semiconductor structure and developed a diode based on tunnel effect.[17] In 1960, following Esaki's work, Ivar Giaever showed experimentally that tunnelling also took place in superconductors. The tunnelling spectrum gave direct evidence of the superconducting energy gap. In 1962, Brian Josephson predicted the tunneling of superconducting Cooper pairs. Esaki, Giaever and Josephson shared the 1973 Nobel Prize in Physics for their works on quantum tunneling in solids.[18][7]In 1981, Gerd Binnig and Heinrich Rohrer developed a new type of microscope, called scanning tunneling microscope, which is based on tunnelling and is used for imaging surfaces at the atomic level. Binnig and Rohrer were awarded the Nobel Prize in Physics in 1986 for their discovery.[19]Tunnelling is the cause of some important macroscopic physical phenomena.Tunnelling is a source of current leakage in very-large-scale integration (VLSI) electronics and results in a substantial power drain and heating effects that plague such devices. It is considered the lower limit on how microelectronic device elements can be made.[20] Tunnelling is a fundamental technique used to program the floating gates of flash memory.Main article: Field electron emissionCold emission of electrons is relevant to semiconductors and superconductor physics. It is similar to thermionic emission, where electrons randomly jump from the surface of a metal to follow a voltage bias because they statistically end up with more energy than the barrier, through random collisions with other particles. When the electric field is very large, the barrier becomes thin enough for electrons to tunnel out of the atomic state, leading to a current that varies approximately exponentially with the electric field.[21] These materials are important for flash memory, vacuum tubes, and some electron microscopes.Main article: Tunnel junctionA simple barrier can be created by separating two conductors with a very thin insulator. These are tunnel junctions, the study of which requires understanding quantum tunnelling.[22] Josephson junctions take advantage of quantum tunnelling and superconductivity to create the Josephson effect. This has applications in precision measurements of voltages and magnetic fields,[21] as well as the multijunction solar cell.Main article: Tunnel diodeA working mechanism of a resonant tunnelling diode device, based on the phenomenon of quantum tunnelling through the potential barriersDiodes are electrical semiconductor devices that allow electric current flow in one direction more than the other. The device depends on a depletion layer between N-type and P-type semiconductors to serve its purpose. When these are heavily doped the depletion layer can be thin enough for tunnelling. When a small forward bias is applied, the current due to tunnelling is significant. This has a maximum at the point where the voltage bias is such that the energy level of the p and n conduction bands are the same. As the voltage bias is increased, the two conduction bands no longer line up and the diode acts typically.[23]Because the tunnelling current drops off rapidly, tunnel diodes can be created that have a range of voltages for which current decreases as voltage increases. This peculiar property is used in some applications, such as high speed devices where the characteristic tunnelling probability changes as rapidly as the bias voltage.[23]The resonant tunnelling diode makes use of quantum tunnelling in a very different manner to achieve a similar result. This diode has a resonant voltage for which a current favors a particular voltage, achieved by placing two thin layers with a high energy conductance band near each other. This creates a quantum potential well that has a discrete lowest energy level. When this energy level is higher than that of the electrons, no tunnelling occurs and the diode is in reverse bias. Once the two voltage energies align, the electrons flow like an open wire. As the voltage further increases, tunnelling becomes improbable and the diode acts like a normal diode again before a second energy level becomes noticeable.[24]Main article: Tunnel field-effect transistorA European research project demonstrated field effect transistors in which the gate (channel) is controlled via quantum tunnelling rather than by thermal injection, reducing gate voltage from 1 volt to 0.2 volts and reducing power consumption by up to 100. If these transistors can be scaled up into VLSI chips, they would improve the performance per power of integrated circuits.[25][26]While the Drude-Lorentz model of electrical conductivity makes excellent predictions about the nature of electrons conducting in metals, it can be furthered by using quantum tunnelling to explain the nature of the electron's collisions.[21] When a free electron wave packet encounters a long array of uniformly spaced barriers, the reflected part of the wave packet interferes uniformly with the transmitted one between all barriers so that 100% transmission becomes possible. The theory predicts that if positively charged nuclei form a perfectly rectangular array, electrons will tunnel through the metal as free electrons, leading to extremely high conductance, and that impurities in the metal will disrupt it.[21]Main article: Scanning tunnelling microscopeThe scanning tunnelling microscope (STM), invented by Gerd Binnig and Heinrich Rohrer, may allow imaging of individual atoms on the surface of a material.[21] It operates by taking advantage of the relationship between quantum tunnelling with distance. When the tip of the STM's needle is brought close to a conduction surface that has a voltage bias, measuring the current of electrons that are tunnelling between the needle and the surface reveals the distance between the needle and the surface. By using piezoelectric rods that change in size when voltage is applied, the height of the tip can be adjusted to keep the tunnelling current constant. The time-varying voltages that are applied to these rods can be recorded and used to image the surface of the conductor.[21] STMs are accurate to 0.001nm, or about 1% of atomic diameter.[24]Main article: Nuclear fusionQuantum tunnelling is an essential phenomenon for nuclear fusion. The temperature in stellar cores is generally insufficient to allow atomic nuclei to overcome the Coulomb barrier and achieve thermonuclear fusion. Quantum tunnelling increases the probability of penetrating this barrier. Though this probability is still low, the extremely large number of nuclei in the core of a star is sufficient to sustain a steady fusion reaction.[27]Main article: Radioactive decayRadioactive decay is the process of emission of particles and energy from the unstable nucleus of an atom to form a stable product. This is done via the tunnelling of a particle out of the nucleus (an electron tunneling into the nucleus is electron capture). This was the first application of quantum tunnelling. Radioactive decay is a relevant issue for astrobiology as this consequence of quantum tunnelling creates a constant energy source over a large time interval for environments outside the circumstellar habitable zone where insolation would not be possible (subsurface oceans) or effective.[27]Quantum tunnelling may be one of the mechanisms of hypothetical proton decay.[28][29]Chemical reactions in the interstellar medium occur at extremely low energies. Probably the most fundamental ion-molecule reaction involves hydrogen ions with hydrogen molecules. The quantum mechanical tunnelling rate for the same reaction using the hydrogen isotope deuterium, D + H2 H + HD, has been measured experimentally in an ion trap.The deuterium was placed in an ion trap and cooled. The trap was then filled with hydrogen. At the temperatures used in the experiment, the energy barrier for reaction would not allow the reaction to succeed with classical dynamics alone. Quantum tunneling allowed reactions to happen in rare collisions. It was calculated from the experimental data that collisions happened one in every hundred billion.[30]Main article: Kinetic isotope effectIn chemical kinetics, the substitution of a light isotope of an element with a heavier one typically results in a slower reaction rate. This is generally attributed to differences in the zero-point vibrational energies for chemical bonds containing the lighter and heavier isotopes and is generally modeled using transition state theory. However, in certain cases, large isotopic effects are observed that cannot be accounted for by a semi-classical treatment, and quantum tunnelling is required. R. P. Bell developed a modified treatment of Arrhenius kinetics that is commonly used to model this phenomenon.[31]By including quantum tunnelling, the astrochemical syntheses of various molecules in interstellar clouds can be explained, such as the synthesis of molecular hydrogen, water (ice) and the prebiotic important formaldehyde.[27] Tunnelling of molecular hydrogen has been observed in the lab.[32]Quantum tunnelling is among the central non-trivial quantum effects in quantum biology.[33] Here it is important both as electron tunnelling and proton tunnelling. Electron tunnelling is a key factor in many biochemical redox reactions (photosynthesis, cellular respiration) as well as enzymatic catalysis. Proton tunnelling is a key factor in spontaneous DNA mutation.[27]Spontaneous mutation occurs when normal DNA replication takes place after a particularly significant proton has tunnelled.[34] A hydrogen bond joins DNA base pairs. A double well potential along a hydrogen bond separates a potential energy barrier. It is believed that the double well potential is asymmetric, with one well deeper than the other such that the proton normally rests in the deeper well. For a mutation to occur, the proton must have tunnelled into the shallower well. The proton's movement from its regular position is called a tautomeric transition. If DNA replication takes place in this state, the base pairing rule for DNA may be jeopardised, causing a mutation.[35] Per-Olov Lowdin was the first to develop this theory of spontaneous mutation within the double helix. Other instances of quantum tunnelling-induced mutations in biology are believed to be a cause of ageing and cancer.[36]Quantum tunnelling through a barrier. The energy of the tunnelled particle is the same but the probability amplitude is decreased.The time-independent Schrdinger equation for one particle in one dimension can be written as 2 2 m d 2 d x 2 (x) + V (x) (x) = E (x) {\displaystyle -{\frac {\hbar ^{2}}{2m}}{\frac {d^{2}}{dx^{2}}}\Psi (x)+V(x)\Psi (x)=E\Psi (x)} or d 2 d x 2 (x) = 2 m 2 (V (x) E) (x) 2 m 2 M (x) (x) , {\displaystyle {\frac {d^{2}}{dx^{2}}}\Psi (x)={\frac {2m}{\hbar ^{2}}}\left(V(x)-E\right)\Psi (x)\equiv {\frac {2m}{\hbar ^{2}}}M(x)\Psi (x),} where {\displaystyle \hbar } is the reduced Planck constant,m is the particle mass,x represents distance measured in the direction of motion of the particle, is the Schrdinger wave function,V is the potential energy of the particle (measured relative to any convenient reference level),E is the energy of the particle that is associated with motion in the x-axis (measured relative to V),M(x) is a quantity defined by V(x) E, which has no accepted name in physics.The solutions of the Schrdinger equation take different forms for different values of x, depending on whether M(x) is positive or negative. When M(x) is constant and negative, then the Schrdinger equation can be written in the form d 2 d x 2 (x) = 2 m 2 M (x) (x) = k 2 (x) , where k 2 = 2 m 2 M . {\displaystyle {\frac {d^{2}}{dx^{2}}}\Psi (x)={\frac {2m}{\hbar ^{2}}}M(x)\Psi (x)=-k^{2}\Psi (x),\qquad {\text{where}}\quad k^{2}=-{\frac {2m}{\hbar ^{2}}}M.} The solutions of this equation represent travelling waves, with phase-constant +k or k. Alternatively, if M(x) is constant and positive, then the Schrdinger equation can be written in the form d 2 d x 2 (x) = 2 m 2 M (x) (x) = 2 (x) , where 2 = 2 m 2 M . {\displaystyle {\frac {d^{2}}{dx^{2}}}\Psi (x)={\frac {2m}{\hbar ^{2}}}M(x)\Psi (x)={\kappa }^{2}\Psi (x),\qquad {\text{where}}\quad {\kappa }^{2}={\frac {2m}{\hbar ^{2}}}M.} The solutions of this equation are rising and falling exponentials in the form of evanescent waves. When M(x) varies with position, the same difference in behaviour occurs, depending on whether M(x) is negative or positive. It follows that the sign of M(x) determines the nature of the medium, with negative M(x) corresponding to medium A and positive M(x) corresponding to medium B. It thus follows that evanescent wave coupling can occur if a region of positive M(x) is sandwiched between two regions of negative M(x), hence creating a potential barrier.The mathematics of dealing with the situation where M(x) varies with x is difficult, except in special cases that usually do not correspond to physical reality. A full mathematical treatment appears in the 1965 monograph by Frman and Frman. Their ideas have not been incorporated into physics textbooks, but their corrections have little quantitative effect.Main article: WKB approximationThe wave function is expressed as the exponential of a function: (x) = e (x) , {\displaystyle \Psi (x)=e^{\Phi (x)},} where (x) + (x) 2 = 2 m 2 (V (x) E) . {\displaystyle \Phi ''(x)+\Phi '(x)^{2}={\frac {2m}{\hbar ^{2}}}\left(V(x)-E\right).} (x) {\displaystyle \Phi '(x)} is then separated into real and imaginary parts: (x) = A (x) + i B (x) , {\displaystyle \Phi '(x)=A(x)+iB(x),} where A(x) and B(x) are real-valued functions.Substituting the second equation into the first and using the fact that the imaginary part needs to be 0 results in: A (x) + A (x) 2 B (x) 2 = 2 m 2 (V (x) E) . {\displaystyle A'(x)+A(x)^{2}-B(x)^{2}={\frac {2m}{\hbar ^{2}}}\left(V(x)-E\right).} Quantum tunneling in the phase space formulation of quantum mechanics. Wigner function for tunneling through the potential barrier U (x) = 8 e 0.25 x 2 {\displaystyle U(x)=8e^{-0.25x^{2}}} in atomic units (a.u.). The solid lines represent the level set of the Hamiltonian H (x , p) = p 2 / 2 + U (x) {\displaystyle H(x,p)=p^{2}/2+U(x)} .To solve this equation using the semiclassical approximation, each function must be expanded as a power series in {\displaystyle \hbar } . From the equations, the power series must start with at least an order of 1 {\displaystyle \hbar ^{-1}} to satisfy the real part of the equation; for a good classical limit starting with the highest power of the Planck constant possible is preferable, which leads to A (x) = 1 k = 0 k A k (x) {\displaystyle A(x)={\frac {1}{\hbar }}\sum _{k=0}^{\infty }\hbar ^{k}A_{k}(x)} and B (x) = 1 k = 0 k B k (x) , {\displaystyle B(x)={\frac {1}{\hbar }}\sum _{k=0}^{\infty }\hbar ^{k}B_{k}(x),} with the following constraints on the lowest order terms, A 0 (x) 2 B 0 (x) 2 = 2 m (V (x) E) {\displaystyle A_{0}(x)^{2}-B_{0}(x)^{2}=2m\left(V(x)-E\right)} and A 0 (x) B 0 (x) = 0. {\displaystyle A_{0}(x)B_{0}(x)=0.} At this point two extreme cases can be considered.Case 1If the amplitude varies slowly as compared to the phase A 0 (x) = 0 {\displaystyle A_{0}(x)=0} and B 0 (x) = 2 m (E V (x)) {\displaystyle B_{0}(x)=\pm {\sqrt {2m\left(E-V(x)\right)}}} which corresponds to classical motion. Resolving the next order of expansion yields (x) C e i d x 2 m 2 (E V (x)) + 2 m 2 (E V (x)) 4 {\displaystyle \Psi (x)\approx C{\frac {e^{i\int dx{\sqrt {{\frac {2m}{\hbar ^{2}}}\left(E-V(x)\right)}}+\theta }}{\sqrt[{4}]{{\frac {2m}{\hbar ^{2}}}\left(E-V(x)\right)}}}} Case 2If the phase varies slowly as compared to the amplitude, B 0 (x) = 0 {\displaystyle B_{0}(x)=0} and A 0 (x) = 2 m (V (x) E) {\displaystyle A_{0}(x)=\pm {\sqrt {2m\left(V(x)-E\right)}}} which corresponds to tunneling. Resolving the next order of the expansion yields (x) C + e + d x 2 m 2 (V (x) E) + C e d x 2 m 2 (V (x) E) 2 m 2 (V (x) E) 4 {\displaystyle \Psi (x)\approx {\frac {C_{+}e^{+\int dx{\sqrt {{\frac {2m}{\hbar ^{2}}}\left(V(x)-E\right)}}}+C_{-}e^{-\int dx{\sqrt {{\frac {2m}{\hbar ^{2}}}\left(V(x)-E\right)}}}}{\sqrt[{4}]{{\frac {2m}{\hbar ^{2}}}\left(V(x)-E\right)}}}} In both cases it is apparent from the denominator that both these approximate solutions are bad near the classical turning points E = V (x) {\displaystyle E=V(x)} . Away from the potential hill, the particle acts similar to a free and oscillating wave; beneath the potential hill, the particle undergoes exponential changes in amplitude. By considering the behaviour at these limits and classical turning points a global solution can be made.To start, a classical turning point, x 1 {\displaystyle x_{1}} is chosen and 2 m 2 (V (x) E) {\displaystyle {\frac {2m}{\hbar ^{2}}}\left(V(x)-E\right)} is expanded in a power series about x 1 {\displaystyle x_{1}} : 2 m 2 (V (x) E) = v 1 (x x 1) + v 2 (x x 1) 2 + {\displaystyle {\frac {2m}{\hbar ^{2}}}\left(V(x)-E\right)=v_{1}(x-x_{1})+v_{2}(x-x_{1})^{2}+\cdots } Keeping only the first order term ensures linearity: 2 m 2 (V (x) E) = v 1 (x x 1) . {\displaystyle {\frac {2m}{\hbar ^{2}}}\left(V(x)-E\right)=v_{1}(x-x_{1}).} Using this approximation, the equation near x 1 {\displaystyle x_{1}} becomes a differential equation: d 2 d x 2 (x) = v 1 (x x 1) (x) . {\displaystyle {\frac {d^{2}}{dx^{2}}}\Psi (x)=v_{1}(x-x_{1})\Psi (x).} This can be solved using Airy functions as solutions. (x) = C A A i (v 1 3 (x x 1)) + C B B i (v 1 3 (x x 1)) {\displaystyle \Psi (x)=C_{A}Ai\left({\sqrt[{3}]{v_{1}}}(x-x_{1})\right)+C_{B}Bi\left({\sqrt[{3}]{v_{1}}}(x-x_{1})\right)} Taking these solutions for all classical turning points, a global solution can be formed that links the limiting solutions. Given the two coefficients on one side of a classical turning point, the two coefficients on the other side of a classical turning point can be determined by using this local solution to connect them.Hence, the Airy function solutions will asymptote into sine, cosine and exponential functions in the proper limits. The relationships between C , {\displaystyle C,\theta } and C + , C {\displaystyle C_{+},C_{-}} are C + = 1 2 C cos (4) {\displaystyle C_{+}={\frac {1}{2}}C\cos {\left(\theta -{\frac {\pi }{4}}\right)}} andQuantum tunnelling through a barrier. At the origin (x = 0), there is a very high, but narrow potential barrier. A significant tunnelling effect can be seen. C = C sin (4) {\displaystyle C_{-}=-C\sin {\left(\theta -{\frac {\pi }{4}}\right)}} With the coefficients found, the global solution can be found. Therefore, the transmission coefficient for a particle tunneling through a single potential barrier is T (E) = e 2 x 1 x 2 d x 2 m 2 [V (x) E] , {\displaystyle T(E)=e^{-2\int _{x_{1}}^{x_{2}}dx{\sqrt {{\frac {2m}{\hbar ^{2}}}\left[V(x)-E\right]}}},} where x 1 , x 2 {\displaystyle x_{1},x_{2}} are the two classical turning points for the potential barrier.For a rectangular barrier, this expression simplifies to: T (E) = e 2 2 m 2 (V 0 E) (x 2 x 1) . {\displaystyle T(E)=e^{-2{\sqrt {{\frac {2m}{\hbar ^{2}}}(V_{0}-E)}}(x_{2}-x_{1})}.} See also: Faster-than-lightSome physicists have claimed that it is possible for spin-zero particles to travel faster than the speed of light when tunnelling.[7] This appears to violate the principle of causality, since a frame of reference then exists in which the particle arrives before it has left. In 1998, Francis E. Low reviewed briefly the phenomenon of zero-time tunnelling.[37] More recently, experimental tunnelling time data of phonons, photons, and electrons was published by Gnter Nimtz.[38] Another experiment overseen by A. M. Steinberg, seems to indicate that particles could tunnel at apparent speeds faster than light.[39][40]Other physicists, such as Herbert Winful,[41] disputed these claims. Winful argued that the wave packet of a tunnelling particle propagates locally, so a particle can't tunnel through the barrier non-locally. Winful also argued that the experiments that are purported to show non-local propagation have been misinterpreted. In particular, the group velocity of a wave packet does not measure its speed, but is related to the amount of time the wave packet is stored in the barrier. Moreover, if quantum tunneling is modeled with the relativistic Dirac equation, well established mathematical theorems imply that the process is completely subluminal.[42][43]Quantum tunneling oscillations of probability in an integrable double well of potential, seen in phase spaceThe concept of quantum tunnelling can be extended to situations where there exists a quantum transport between regions that are classically not connected even if there is no associated potential barrier. This phenomenon is known as dynamical tunnelling.[44][45]The concept of dynamical tunnelling is particularly suited to address the problem of quantum tunnelling in high dimensions (d>1). In the case of an integrable system, where bounded classical trajectories are confined onto tori in phase space, tunnelling can be understood as the quantum transport between semi-classical states built on two distinct but symmetric tori.[46]Chaos-assisted tunnelling oscillations between two regular tori embedded in a chaotic sea, seen in phase spaceIn real life, most systems are not integrable and display various degrees of chaos. Classical dynamics is then said to be mixed and the system phase space is typically composed of islands of regular orbits surrounded by a large sea of chaotic orbits. The existence of the chaotic sea, where transport is classically allowed, between the two symmetric tori then assists the quantum tunnelling between them. This phenomenon is referred as chaos-assisted tunnelling.[47] and is characterized by sharp resonances of the tunnelling rate when varying any system parameter.When {\displaystyle \hbar } is small in front of the size of the regular islands, the fine structure of the classical phase space plays a key role in tunnelling. In particular the two symmetric tori are coupled "via a succession of classically forbidden transitions across nonlinear resonances" surrounding the two islands.[48]Several phenomena have the same behavior as quantum tunnelling. Two examples are evanescent wave coupling[49] (the application of Maxwell's wave-equation to light) and the application of the non-dispersive wave-equation from acoustics applied to "waves on strings".[citation needed]These effects are modeled similarly to the rectangular potential barrier. In these cases, one transmission medium through which the wave propagates that is the same or nearly the same throughout, and a second medium through which the wave travels differently. This can be described as a thin region of medium B between two regions of medium A. The analysis of a rectangular barrier by means of the Schrdinger equation can be adapted to these other effects provided that the wave equation has travelling wave solutions in medium A but real exponential solutions in medium B.In optics, medium A is a vacuum while medium B is glass. In acoustics, medium A may be a liquid or gas and medium B a solid. For both cases, medium A is a region of space where the particle's total energy is greater than its potential energy and medium B is the potential barrier. These have an incoming wave and resultant waves in both directions. There can be more mediums and barriers, and the barriers need not be discrete. Approximations are useful in this case.A classical wave-particle association was originally analyzed as analogous to quantum tunneling,[50] but subsequent analysis found a fluid dynamics cause related to the vertical momentum imparted to particles near the barrier.[51]Dielectric barrier dischargeField electron emissionHolsteinHerring methodProton tunnelingQuantum cloningSuperconducting tunnel junctionTunnel diodeTunnel junctionWhite hole^ Lerner; Trigg (1991). Encyclopedia of Physics (2nded.). New York: VCH. p.1308. ISBN978-0-89573-752-6.^ Davies, P C W (6 May 2004). "Quantum mechanics and the equivalence principle". Classical and Quantum Gravity. 21 (11): 27612772. arXiv:quant-ph/0403027. Bibcode:2004CQGra..21.2761D. doi:10.1088/0264-9381/21/11/017. ISSN0264-9381. But quantum particles are able to tunnel into the classically forbidden region ...^ Fowler, Michael (5 December 2019). "Particle in a Finite Box and Tunneling". LibreTexts Chemistry. Retrieved 4 September 2023. 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