Quantum tunneling effect and its applications in semiconductor Devices

Hengrui Liu [*]

Beijing Royal School, Beijing, China

* Corresponding Author Email: liuhengrui@st.brs.edu.cn

Abstract. The quantum tunneling effect is a classical phenomenon in quantum physics, which allows tiny particles to pass through seemingly insurmountable energy barriers, breaking the rule of "energy determines motion" in classical mechanics. This discovery not only changed scientists' understanding of the microscopic world, but also played a key role in semiconductor technology. For example, tunneling diodes use this effect to enable fast current switching, while newer transistors, such as TFET, reduce power consumption by controlling particle tunneling. In addition, flash memory devices also rely on quantum tunneling to store data, making electronic devices more power-efficient and smaller. This article explains how to calculate the probability of a particle crossing an obstacle and details the three major applications of quantum tunneling in semiconductors: high-speed switching, low-power circuitry, and high-efficiency storage. The article also explores possible future developments, such as the use of tunneling effects to manipulate information in quantum computers, or the use of new materials to further reduce energy losses. These studies provide an important direction for the innovation of next-generation electronic devices.

Keywords: Quantum tunneling effect, semiconductor, barrier.

1. Introduction

The quantum tunneling of microscopic particles is a typical effect and an important issue that needs to be dealt with in many electronic component designs, which has attracted more and more attention [1-2]. The quantum tunneling effect refers to the fact that when the energy of a particle is lower than the barrier, microscopic particles can still pass through the barrier with a non-zero probability. This discovery has changed people's long-standing inherent view that "energy determines the boundaries of motion". This effect was discovered by Friedrich Hond in 1927, giving people a greater understanding of the behavior of microscopic particles [3]. Since then, in 1928, George Gamow first used the quantum tunneling effect to explain alpha decay, explaining the reason why particles can escape the junction of atomic nuclei in common nuclear fusion [4]. After that, the quantum tunneling effect gradually became the basic tool in condensed matter physics, nanoelectronics, and information [5]. It can be said that the quantum tunneling effect is a bridge connecting microscopic particles with macroscopic quantum technology. In terms of semiconductor technology, with the innovation of semiconductor devices, the impact of the quantum tunneling effect on its performance has become more significant. At the same time, the conductivity switching characteristics of the quantum tunneling effect also provide new ideas for designing new tunnel semiconductor devices.

This paper reviews the theory and occurrence conditions of particle behavior description when particles pass through barriers in classical physics and quantum physics, describes different calculation methods of probability waves in the quantum tunneling effect and the probability calculation of microscopic particles in different barriers, and summarizes existing relevant research results, focuses and in-depth analysis of the application methods of this effect in the semiconductor field, and also looks forward to the cutting-edge application of this principle in the future.

2. Theoretical analysis of tunneling effect

2.1. Comparison of the description of barrier penetration between classical and quantum physics

In classical mechanics that are familiar to people, if an object wants to cross a potential barrier, it needs to have energy higher than the potential barrier, consume its energy and convert it into potential energy, reach the top of the potential barrier, and then return energy under the action of potential energy to complete the crossing, otherwise, it will not be able to cross the potential barrier and reach the other end, so the range of motion of the particle is limited. In quantum physics, by solving the one-dimensional Schrödinger equation, the probability wave function representing microscopic particles will not only be reflected, but is due to the uncertainty and wave-particle duality of microscopic particles in quantum physics theory. Although the amplitude is greatly reduced, this wave function can directly pass through the barrier. This means that the microscopic particles themselves can also have a certain probability of "tunneling" and directly passing through the potential barrier, as shown in figure 1.

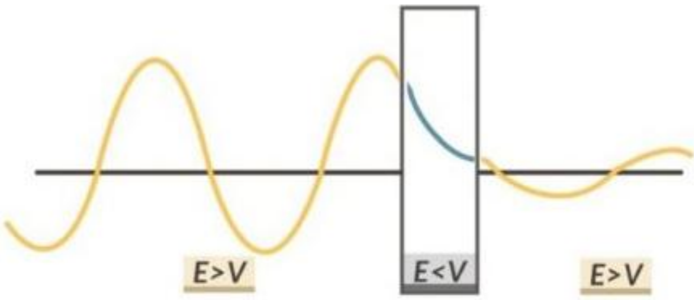


Figure 1. Quantum tunneling diagram

2.2. Tunnel probability calculation

In order to calculate the probability of quantum tunneling and verify the existence of this effect, we need to represent the particle wave functions on the two sides of the potential barrier and see if the probability wave function at the other end of the barrier is zero. We can use the segmented function to represent the probability wave functions at both ends of the barrier. Starting by assuming that the barrier thickness is a, the particle wave function before the barrier should be added to the incident wave and the reflected wave, while the tunneling is the wave function of the projected wave.

Using the steady-state wave function formula, both functions is expressed as: $\Psi(\mathrm{x}) = \mathrm{e}^{\frac{\mathrm{ipx}}{\hbar}}$ Written using the de Broglie relation formula: $\mathrm{p} = \hbar\mathrm{k}$, Then $\Psi(\mathrm{x}) = \mathrm{e}^{\mathrm{ikx}}$, where k is the wave vector. The piecewise function is:

$$\begin{cases} Ae^{ki} + Be^{ki} & x < 0 \\ \quad Ce^{ki} & x > a \end{cases} \tag{1}$$

$\mathrm{Ae}^{\mathrm{ki}}$is the wave function of the incident wave, $\mathrm{Be}^{\mathrm{ki}}$the wave function of the reflected wave and $\mathrm{Ce}^{\mathrm{ki}}$ the wave function of the transmitted wave.

According to the one-dimensional probabilistic flow density formula:

$$J_x = \frac{i\hbar}{2\mu}\left[\Psi(x)\frac{d}{dx}\Psi^*(x) - \Psi^*(x)\frac{d}{dx}(x)\right] \tag{2}$$

Substituting the incident wave function above yields:

$$j_A = \frac{i\hbar}{2\mu}\left[Ae^{ikx}\frac{d}{dx}(A^*e^{-ikx}) - A^*e^{-ikx}\frac{d}{dx}(Ae^{ikx})\right] \tag{3}$$

$$j_A = [|A|^2(-ik) - |A|^2(ik)] \tag{4}$$

$$j_A = \frac{\hbar k}{\mu}|A|^2 \tag{5}$$

Therefore, the probability flow density of a transmitted wave is:

$$j_C = \frac{\hbar k}{\mu}|C|^2 \tag{6}$$

Then the transmission probability of the barrier can be expressed as their ratio:

$$\frac{j_c}{j_A} = \left|\frac{C}{A}\right|^2 \tag{7}$$

When the barrier is much larger than the incident particle energy E, the transmission probability can be approximate:

$$\left|\frac{C}{A}\right|^2 \approx 16\left(\frac{E}{V_0}\right)\left(1-\frac{E}{V_0}\right)e^{-2\alpha\sqrt{\frac{2\mu(V_0-E)}{\hbar^2}}} \tag{8}$$

Where $\alpha$is the thickness of the barrier, V_0 is the barrier hight, E is the energy of the particle, $\hbar$ is the reduced Planck constant which is equal to $\frac{h}{2\pi}$, so there will be particles tunneling through the potential barrier, by analyzing this symmetry barrier.

3. Application of tunneling effect

Quantum tunneling, as a fundamental quantum mechanical phenomenon, enables particles to traverse energy barriers that have traditionally been insurmountable. The probability of such a tunnel event depends largely on the geometric characteristics of the underlying obstacle, including its shape, height, width, and spatial layout. By strategically modifying these parameters, researchers can precisely design tunnel probabilities, unlocking new capabilities across disciplines. Below, we detail how the longitudinal barrier configuration and multiplicity facilitate different applications.

3.1. Utilization and applications of tunneling effect in semiconductors

In 1985, Capasso F et al. proposed that when a minority carrier high-energy injection can produce quantum tunneling with a transmission coefficient of 1, and at the same time, it can cause the semiconductor to show that the current decreases with the increase of voltage (NDR phenomenon).

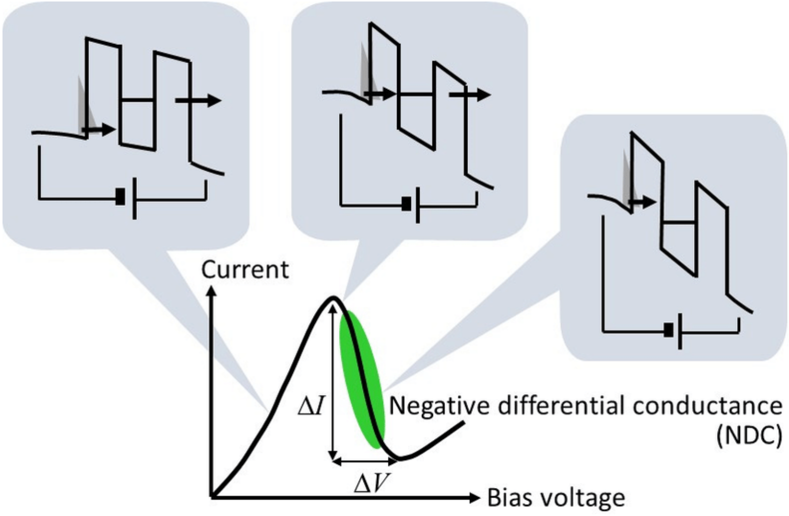


Figure 2. The current-voltage image of the NDR effect

It exhibits negative resistance and produces negative conductivity [6]. The Ezaki diode uses this principle. It is also called a tunnel diode. It is made of a mixture of gallium arsenide and potassium antimonide to form a pn junction. Due to the quantum tunneling effect, the electrons in the semiconductor can pass through the semiconductor without obtaining a voltage higher than the barrier. Therefore, it is fast and has good conductivity and switching, with tunneling current as the main current. This discovery also allowed Ezaki and his companions to win the Nobel Prize in Physics.

After this, Summers and Brennan used the "interband tunneling" caused by the superposition of the quantum states by adjusting the width of potential barriers in the semiconductor and designing the coupling of quantum states, thereby improving the efficiency of carrier tunneling [6], and the tunneling field effect transistor was also generated [7]. This transistor regulates the electric field by biasing the voltage and controls the occurrence of band tunneling by the gate. This process is different from direct tunneling in that it is not affected by the heat distribution and its requirements for power supply voltage are relatively small. With the deepening of the research and attempts at the quantum tunneling phenomenon, resonant tunneling diodes emerged. Since the first detection of negative resistance in a double-barrier quantum well in a laboratory, this phenomenon has been actively applied to semiconductors [8]. The uniqueness of the dual barrier quantum well structure of RTD is that under the action of mechanics, a built-in electric field will be generated in the structure to affect the quantum energy states in the circuit, and the current-voltage curve will also change. Therefore, a method is produced to use mechanical signals to control resistance changes and tunneling current within a certain bias range. Mao Hiyang and others also conducted experiments and drew current-voltage images for different semiconductor materials [9].

However, the existence of the quantum tunneling effect is both an opportunity for technological innovation and a challenge and problem in the performance of many microelectronic devices. When the thickness of the gate oxide layer of the MOSFET is reduced to less than 3 nanometers, due to the quantum tunneling effect, the leakage current will directly pass through the insulating layer. This phenomenon directly affects the power consumption of the device, leads to current loss, and adds a limit on the thickness of the oxide layer. According to the capacitor formula: In order to maintain high capacitance, the device needs to continuously reduce the thickness of the oxide layer. When the oxide layer decreases to a certain extent, the current density passing through the insulating layer will gradually increase due to the thinning of the barrier thickness, resulting in a decrease in power loss and reliability. This contradiction undoubtedly becomes an obstacle to the development of component manufacturing. To solve this problem, the researchers introduced High-k material to replace traditional silicon oxide, aiming to maintain high capacitance by increasing the dielectric constant of the material, rather than reducing its thickness [10]. After replacement, the probability of tunneling is significantly reduced, and the leakage current phenomenon is significantly reduced, and the contradiction is also resolved [11].

At the same time, the application of the quantum tunneling effect in flash memory is in a different way from the above, and is mainly used to control the tunneling of charges to Floating Gate for the writing and erasing of the memory [12].

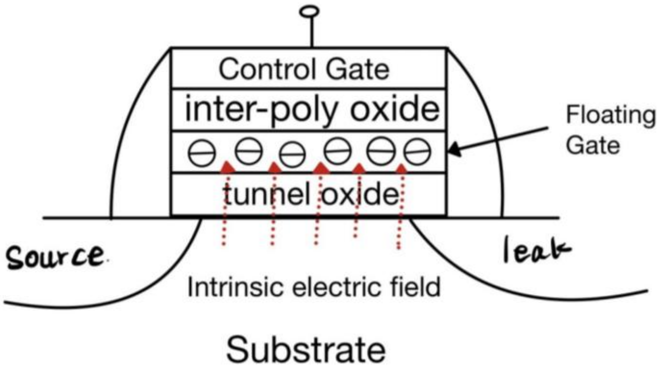
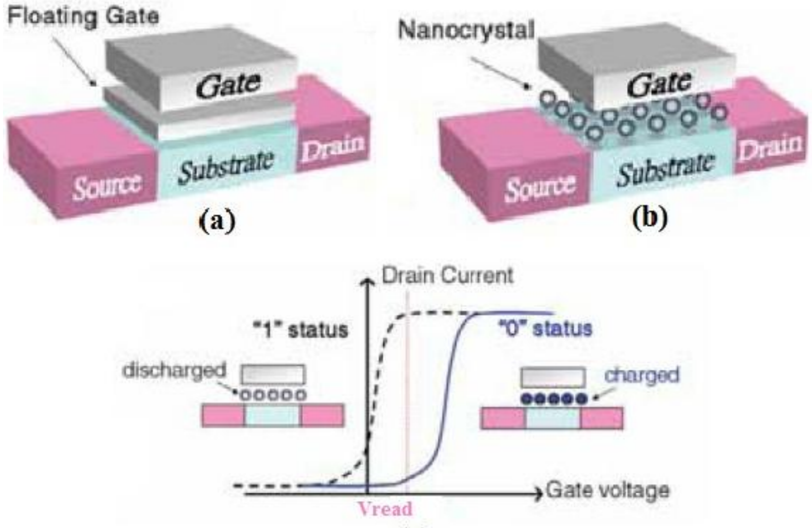


Figure 3. Schematic diagram of the Floating Gate FET

As shown in figure 3, the flash memory is designed with a Floating Gate FET, which consists of four parts: Control Gate, Flow Gate, leak, and source. The Floating Gate is not connected to a circuit and can be used to store the charge in the transistor, which changes the conductivity of the entire transistor. In the “writing” process, as shown in the figure, because of the input of the power supply, the voltage above is higher than that below, and with the increase of voltage, the tunneling probability of electrons increases, at this time, the electrons pass through the barrier, enter a layer of floating gate below, and are stored in the floating gate layer, which is regarded as writing and recorded as "1"; In the "erase" process, the direction of the potential difference is reversed, and the lower part is converted to a higher potential position, so that the electrons tunnel through the oxide layer in the device again and return to their original position in the semiconductor, which is denoted as "0", As shown in figure 4.



(a) (b)

(c)

Figure 4. The figure shows the schematic diagram of the write-and-erase status

The advantages of this method are: first, because of the unique mechanism of quantum tunneling when crossing the barrier, it requires less energy than traditional electron propagation, so the energy required for storage is relatively small. Second, compared with the traditional use of wires, the design of the floating gate is more concise and the structure is simpler, so it facilitates the future increase of memory density and promotes the reduction of the volume of related components. Third, compared with direct injection of hot electrons, the electron tunneling method has less damage to the device and is faster, which improves the device's lifetime and also improves the device's performance [14].

In summary, the application of the quantum tunneling effect in semiconductors is mainly reflected in its performance: first, under the action of an electric field, charged particles tunnel through the element, so that the conductivity value can switch between high conductivity and low conductivity, which is also known as the conductivity switching effect. Second, the effect of the change of the thickness and number of potential barriers on the quantum tunneling ability is that when the NDR effect occurs, the current-voltage image will change due to the change of the potential barrier, so that the semiconductor presents different resistance curves. These characteristics determine the important position of the tunneling effect in the development of semiconductor technology.

4. Cutting-edge analysis

In the field of quantum computing, superconducting qubits have realized the superposition and manipulation of quantum states through the regulation of tunneling behavior, which has given rise to the research and development of many quantum systems. At the same time, in molecular chemistry simulation, quantum tunneling-related simulations provide people with new perspectives. In the future, tunneling technology will be further integrated into quantum computing and continue to contribute to the development of quantum physics and information technology.

4.1. Application of the quantum tunneling effect in qubit

In superconducting quantum computers, the role of quantum tunneling is mainly reflected in the Josephson junction in the qubits. The structure is shown in Figure 5, where the two superconductors are separated by insulators, according to the Josephson effect, due to the low barrier between the superconductors, electrons can tunnel to produce current, even in the absence of voltage, and this

Josephson junction will have a voltage step on the current-voltage curve under microwave irradiation at a certain frequency [15].

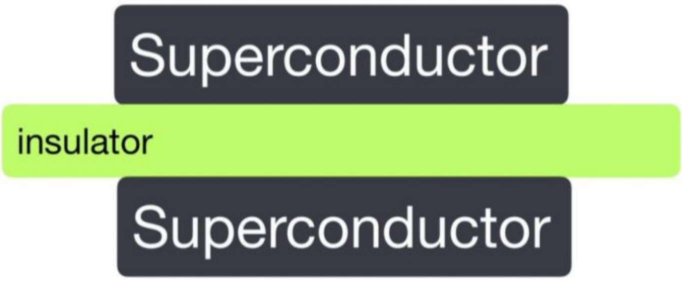


Figure 5. Schematic diagram of Josephson's knot

Therefore, the application of microwave pulses of a specific frequency can induce quantum state tunneling transitions, so that qubits can quickly make periodic transitions, and by adjusting the phase, the qubits can be placed in a superposition state, which also improves the stability of quantum computing [15].

4.2. Application of the quantum tunneling in the simulation of electron transfer between molecules

The essence of this is to map the intermolecular quantum tunneling into controllable quantum devices, such as the tunneling reaction of hydrogen molecules with deuterium ions [16], Roland Wester's team introduced deuterium into the ion trap and filled it with hydrogen after cooling, because there is not enough thermal energy, the reaction between the two species cannot occur under classical physics, and studies have shown that although the number is small, The production of hydrogen ions (about 5.2 by 10 to the minus 20 cubic centimeters per second) can still be detected, which means that the reaction between the hydrogen molecule and the deuterium ion has occurred due to the quantum tunneling effect. This achievement not only verifies the universality of quantum tunneling under extreme conditions, but also provides a high-precision experimental benchmark for molecular dynamics simulation [16].

5. Conclusion

As a bridge between the microscopic world and macroscopic technology, the quantum tunneling effect has deepened people's understanding of the behavior of microscopic particles, and has given birth to the technological innovation of many electronic components, then enabled groundbreaking innovations across different fields. From tunneling diodes to qubits, showing the infinite power of the quantum mechanical theory and the crystallization of physicists' wisdom. In this paper, we systematically sort out three application paradigms of tunneling effect in the field of semiconductors: tunnel diodes achieve high-speed switching characteristics through negative differential resistance; Tunneling field-effect transistors use interband tunneling to break through the subthreshold swing limit. Floating-gate flash memory uses tunneling current to store and erase low-power charges. As the size of semiconductor devices approaches the nanoscale, the leakage current problem caused by the quantum tunneling has become a key bottleneck restricting the reliability of the device, and the introduction of high dielectric constant (High-k) materials can reduce the tunneling probability. In the future, this effect will also be widely used in quantum computing and molecular dynamics to play a unique role.

In the future, people will further realize efficient tunneling control, and explore new material systems and structures, so as to realize the full potential of quantum tunneling in fields including quantum computing and molecular dynamics.

References

[1] Gong Jian, Yang Fuhua, Feng Songlin. Coherent tunneling in coupled quantum wells under a uniform magnetic field [J]. Chin. Phys. Lett., 2007, 24 (8): 2383 - 2386.

[2] Saffarzadeh A, Bahar M, Banihasan M. Spin-dependent resonant tunneling in ZnSe/ZnMnSe heterostructures [J]. Physica E, 2005, 27 (4): 462 - 468.

[3] HandWiki. Friedrich Hund. In Encyclopedia. https://encyclopedia.pub/entry/35220.

[4] Stuewer, R.H. (1986). Gamow's Theory of Alpha-Decay. In: Ullmann-Margalit, E. (eds) The Kaleidoscope of Science. Boston Studies in the Philosophy of Science, vol 94. Springer, Dordrecht. https://doi.org/10.1007/978-94-009-5496-0_14.

[5] ABRAHAM N, WATANABE K, TANIGUCHI T, et al. A high-quality entropy source using van der Waals heterojunction for true random number generation [J]. ACS Nano, 2022, 16 (4): 5898 - 5908.

[6] Capasso F, Kiehl R A. Resonant tunneling transistor with quantum well base and high energy injection: a new negative differential resistance device [J]. J Appl Phys, 1985; 58 (3): 1366.

[7] Summers C J, Brennan K F. Variably spaced super-lattice energy filter, a new device design concept for high-energy electron injection [J]. Appl Phys Lett 1986; 48 (12): 806.

[8] Wang Y, Zhang L, Cao J, et al. Research on electrostatic discharge characteristics of tunnel field effect transistors. Acta Phys Sin, 2014, 63: 178501.

[9] Mao, H. Y, Zhang, W. D., Xiong, J. J., & Xue, C. Y. (2006). Consistency testing and research on I-V characteristics of resonant tunneling diodes. Chinese Journal of Scientific Instrument, (Suppl. 2), 3.

[10] Mao, H., Xiong, J., Zhang, W., Xue, C., Sang, S., & Bao, A. (2006). Piezoresistive characteristics testing and research of resonant tunneling diodes. Journal of Semiconductors.

[11] Kuang, Q. W. (2013). Study on ALD-deposited high-k gate dielectric materials and device characteristics [Doctoral dissertation, Xi'an University of Electronic Science and Technology, China].

[12] Chang, J. H. C. M. P. (2011). Development of hafnium based high-k materials—a review. Materials Science and Engineering: R: Reports.

[13] Srivastava, Anurag & Tyagi, Neha. (2012). Semiconductor Nanocrystals. 10.5772/50440.

[14] Lee, J. S. (2011). Review paper: nano-floating gate memory devices. Electronic Materials Letters, 7 (3), 175 - 183.

[15] Kuang, Q. W. (2013). Study on ALD-deposited high-k gate dielectric materials and device characteristics [Doctoral dissertation, Xi'an University of Electronic Science and Technology, China].

[16] Wild, R., Nötzold, M., Simpson, M. et al. Tunnelling measured in a very slow ion-molecule reaction. Nature615,425 - 429 (2023). https://doi.org/10.1038/s41586 - 023 - 05727 - z.