Theoretical Study of Quantum Tunneling in Semiconductor Devices

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Abstract

Quantum tunneling is one of the most important quantum-mechanical effects used in modern electronics. Although classical physics predicts that a particle with energy lower than a barrier cannot cross it, quantum theory shows that there is still a finite probability of penetration through a thin barrier. This principle explains the operation of tunnel diodes, resonant tunneling structures, scanning tunneling systems, flash memory devices, and many leakage processes found in scaled transistors. The present paper gives a theoretical study of quantum tunneling in semiconductor devices using a simple analytical approach based on barrier width, barrier height, carrier effective mass, and applied electric field. The discussion is focused on how tunnelling probability changes with device dimensions and why this effect becomes stronger as semiconductor structures move to the nanometer scale. The paper also compares useful tunneling with unwanted tunneling leakage and explains why this phenomenon is both a design challenge and an engineering opportunity. Theoretical results show that thinner barriers and lower effective mass strongly increase transmission probability, leading to faster switching in some special devices but also higher off-state current in conventional transistors. This study highlights the continued importance of quantum tunneling in semiconductor research and design.

Introduction

Semiconductor devices are the foundation of modern communication, computing, sensing, and power systems. For many years, their behavior could be explained largely by classical ideas such as drift, diffusion, and standard energy band theory. However, when device dimensions are reduced to the nanometer range, quantum effects begin to play a direct role in charge transport. Among these

effects, quantum tunneling is especially significant because it allows electrons or holes to pass through a potential barrier even when their energy is lower than the barrier height. This behavior is impossible in classical mechanics, but it is a natural consequence of the wave nature of matter.
In practical semiconductor engineering, tunneling can be useful or harmful. It is useful in devices such as the Esaki tunnel diode, where tunneling creates negative differential resistance and enables high-speed operation (Esaki, 1958). It is also central to resonant tunneling devices and charge storage mechanisms in memory technologies. At the same time, tunneling can create gate leakage, junction leakage, and reliability problems in highly scaled MOSFETs and thin-oxide structures (Sze & Ng, 2006). Therefore, a theoretical understanding of this effect is essential for device design.

Background
Quantum tunneling arises from the Schrödinger equation, where a particle's wave function penetrates and decays within a potential barrier instead of vanishing at its edge. The transmitted wave gives a finite probability (its square) of crossing the barrier, so even classically forbidden regions can allow current if the barrier is sufficiently thin.
Historically, tunneling became important in semiconductor physics after the development of heavily doped p-n junctions. Esaki showed that narrow junctions in germanium could support tunneling current, creating the tunnel diode (Esaki, 1958). Later, tunneling through artificial superlattices and thin barriers led to resonant tunneling concepts (Tsu & Esaki, 1973). In present-day devices, tunneling is strongly linked with nanoscale dimensions, high electric fields, and ultra-thin dielectric layers. It is also influenced by band alignment, effective mass, and interface quality. Therefore, tunneling is not only a basic quantum concept but also a practical issue in semiconductor technology (Ferry, 2000; Lundstrom, 2000).

Methodology
This paper follows a theoretical and analytical method rather than an experimental one. The discussion begins with a one-dimensional rectangular energy barrier model, which is commonly used to explain direct tunneling in semiconductors. A carrier with energy E is incident on a barrier of height V0 and width a, where $V_0 > E$. Under these conditions, the transmission probability can be approximated by an exponential expression. The model captures the main dependence of tunneling on barrier shape and material parameters.
A simplified Wentzel-Kramers-Brillouin (WKB) approach is used to interpret the effect of changing barrier width, barrier height, and carrier effective mass. The analysis is qualitative but physically meaningful. Barrier width represents the

thickness of depletion or oxide regions, barrier height represents the energy separation that the carrier must penetrate, and effective mass represents how the carrier responds to the crystal environment. Theoretical comparison is then made between ordinary transport, where carriers go over the barrier, and tunneling transport, where carriers pass through it. This method helps explain why scaling down device size makes tunneling more important even when the barrier material remains unchanged.

$$T \approx \exp(-2\kappa a)$$

$$\kappa = \sqrt{[2m^*(V_0 - E)]} / \hbar$$

Results & Discussion

The analysis shows that tunneling probability is highly sensitive to barrier width: even a slight reduction greatly increases transmission due to the exponential decay of the wave inside the barrier. As a result, nanometer-scale oxides and junctions in semiconductor devices can exhibit significant tunneling current, making this effect unavoidable with continued miniaturization.

Barrier height is the second key factor: higher barriers reduce transmission, while lower ones increase it. In real materials, this depends on band structure, doping, oxide type, and interface quality. Thus, material selection is crucial, with approaches like high-k dielectrics and optimized gate stacks used to control leakage while maintaining device performance.

The third result concerns effective mass. A lower carrier effective mass increases tunneling probability because the carrier behaves more like a delocalized quantum wave. Materials with smaller effective mass may therefore show stronger tunneling for the same barrier geometry. This is one reason why device behavior differs from one semiconductor system to another.

This relation shows that tunneling depends exponentially on the product of decay constant and barrier width. The decay constant itself depends on effective mass and the difference between barrier height and carrier energy. Therefore, width, mass, and energy separation all act together.

From a device point of view, the same quantum effect can lead to opposite outcomes. In tunnel diodes, strong tunneling is desirable because it produces high-speed response and a region of negative differential resistance that is useful in oscillators and switching circuits. In flash memory, tunneling helps move charge through thin oxide layers during write and erase operations. In contrast, for modern MOSFETs, direct gate tunneling and band-to-band tunneling can increase standby power loss and reduce efficiency. Thus, tunneling must be enhanced or suppressed depending on the purpose of the device.

A further important point is that tunneling cannot be fully understood by geometry alone. Real devices include non-ideal interfaces, trap states, imageforce barrier lowering, and field-induced barrier deformation. Under a high electric field, a triangular barrier may form, leading to Fowler-Nordheim tunneling instead of simple direct tunneling. Even so, the basic theoretical lesson remains the same: the smaller and thinner the structure, the more dominant quantum transport becomes. This is why classical-only modeling becomes insufficient for deeply scaled semiconductor devices.

Conclusion

Quantum tunneling is a fundamental phenomenon that strongly influences the behavior of semiconductor devices, especially at reduced dimensions. This theoretical study shows that tunneling probability rises sharply when barrier width decreases, barrier height decreases, or carrier effective mass becomes smaller. These trends explain both the useful operation of special devices such as tunnel diodes and the undesired leakage found in ultra-scaled transistors. The study also shows that quantum tunneling is not simply a correction to classical transport; in many nanoscale structures it becomes a primary conduction mechanism.

Future Scope

Future work can extend this study by using numerical simulations for realistic barrier shapes, multi-layer semiconductor systems, and temperature-dependent effects. Additional research may also focus on tunneling in two-dimensional materials, quantum wells, and low-power device architectures. A better understanding of tunneling will help engineers design semiconductor components that balance speed, memory performance, and energy efficiency in next-generation electronics.

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