

Schottky Barrier Diode's as Enablers of Scalable Quantum Computing Hardware

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Abstract: Scalable quantum computing hardware necessitates electronic components that integrate ultra-fast switching, minimal leakage, and energy-efficient performance at Nano scale dimensions. This study examines Schottky barrier diodes (SBDs) as pivotal devices for scalable quantum computing hardware through quantum-aware device simulations utilizing Indium Phosphide (InP) as the semiconductor platform. Quantum transport mechanisms, such as WKB-based tunneling and quasi-ballistic carrier transport, are included to accurately represent device behavior beyond the classical thermionic emission regime. Simulation findings indicate that the modulation of engineered barrier height decreases the Schottky barrier from 0.65 eV to 0.45 eV, resulting in a 54% decrease in switching delay from 1.2 ps to 0.55 ps. The forward current density rises from 1.8×10^4 A/cm² to 6.2×10^4 A/cm² at an operating bias of 0.25 V, whereas the reverse leakage current density is reduced by nearly in order of magnitude at -0.05 V. These findings illustrate that InP-based Schottky barrier diodes provide high-speed, low-power operation and consistent performance, positioning them as promising elements for quantum control, readout circuitry, and scalable hybrid quantum-classical computing architectures.

Keywords: Schottky barrier diode, Quantum transport, Indium phosphide, barrier height engineering, Quantum computing hardware

INTRODUCTION: The rapid evolution of quantum computing has generated a heightened demand for electronic hardware capable of functioning at ultra-high speeds, low power levels, and cryogenic temperatures, while also maintaining scalability and reliability. Alongside the qubits, classical electronic components are crucial in quantum computing systems, especially in control, readout, and signal-conditioning circuits that connect with quantum processors, conventional CMOS technologies encounter significant obstacles in these scenarios due to increased power dissipation, latency, and performance deterioration at low temperatures [1, 2]. Schottky barrier diodes (SBDs) have been recognized for a long time as essential components in high-frequency rectification, detection, and switching applications due to their majority-carrier transport, minimal junction capacitance and rapid response times [3, 4]. Among the various semiconductor materials, Indium Phosphide (InP) stands out as a particularly appealing option because of its high electron mobility, low effective mass, and superior transport

properties, which facilitate operation in the sub-picoseconds range [5, 6]. These characteristics position InP-based SBDs as strong candidates for cryogenic and quantum-adjacent electronic applications. When device dimensions are miniaturized to the nanometer scale, classical thermionic emission models are no longer sufficient to characterize carrier transport at metal-semiconductor interfaces. Instead, quantum transport mechanisms, including tunneling, carrier confinement, and quasi-ballistic conduction, become dominant current flow [7]. In particular, the engineering of barrier heights and the quality of interfaces play a crucial role in determining tunneling probabilities and switching behaviors, which directly influence device speed and leakage characteristics. Consequently, analytical and numerical methods, such as Wentzel-Kramers-Brillouin (WKB) tunneling and quantum-aware transport models, have become vital for accurate performance predictions [8, 9]. Recent research has underscored the significance of low-noise, low-latency Schottky devices for cryogenic applications and hybrid quantum-classical architectures, where classical electronics must operate alongside sensitive quantum systems [10, 11]. Nevertheless, a comprehensive study of InP Schottky barrier diodes that include quantum transport effects and emphasizes their function as essential components for scalable quantum computing hardware is still lacking. In this paper, we present a detailed simulation-oriented analysis of InP Schottky barrier diodes, incorporating WKB-based tunneling and quasi-ballistic transport to evaluate their performance beyond classical boundaries. We assess the effects of barrier height modulation, operating bias, and device scaling on switching delay, current density, and leakage behavior. The results illustrate that quantum-engineered InP SBDs can achieve ultra-fast, low-power operation, supporting their integration into quantum control and readout circuitry for scalable quantum computing platforms.

DEVICE STRUCTURE AND SIMULATION METHODOLOGY: The schottky barrier diode (SBD) analyzed in this work is based on an InP, which was chosen for its high electron mobility and favorable transport features at Nano scale dimensions. This device includes metal-semiconductor junction that is formed on an n-type InP epitaxial layer, which is grown on a heavily doped n⁺ InP substrate to maintain low series resistance. A schematic cross-sectional depiction of the simulated structure can be found in figure 1.

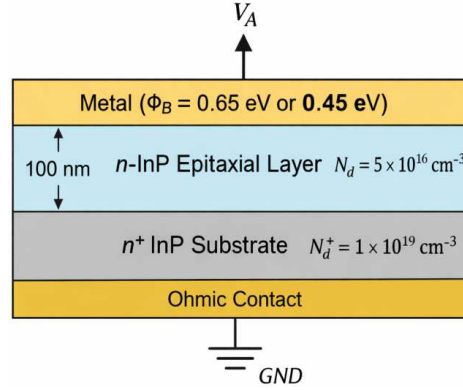


Figure 1: Cross-sectional view of the simulated InP Schottky Barrier Diode structure

The Schottky contact is established using a low-work function metal, which facilitates controlled modulation of the Schottky barrier height. By selecting appropriate metals and employing interface engineering, the effective barrier height is adjusted from 0.65 eV (Conventional) to 0.45 eV (engineered) to investigate its effects on quantum transport and switching performance. The classical thermionic emission current density is expressed as:

$$J_{TE} = A^* T^2 \exp\left(-\frac{q\phi_B}{KT}\right) \left[\exp\left(\frac{qV}{nkT}\right) - 1\right] \quad (1)$$

Where A^* is the Richardson constant for InP, ϕ_B is the Schottky barrier height, V is the applied bias, n is the ideality factor, K is the Boltzmann's constant and T is Temperature. As device dimensions are scaled and operating temperatures are reduced, this classical description becomes insufficient, motivating the inclusion of quantum tunneling effects. An ohmic contact is presumed at the bottom n^+ region, ensuring optimal carrier injection and extraction. The lateral device's dimensions are optimized to the sub-micron scale to decrease parasitic capacitance and transit time effects, in accordance with the requirements of ultra-fast and cryogenic electronics. WKB-based tunneling is employed to simulate carrier transmission through the Schottky barrier, especially under forward bias conditions where tunneling-assisted transport plays a crucial role. To accurately capture carrier transport in the nanoscale regime, WKB tunneling is incorporated to model electron transmission through the Schottky barrier. The tunneling probability $T(E)$ is given by:

$$T(E) = \exp\left[-\frac{2}{\hbar} \int_{x_1}^{x_2} \sqrt{2m^*(V(x) - E)} dx\right] \quad (2)$$

Where m^* effective mass in InP, \hbar is the reduced Planck constant, $V(x)$ is the spatially varying Schottky barrier potential, and E is the carrier energy. The total tunneling current density is then obtained by energy integration:

$$J_{tunnel} = \frac{q}{2\pi^2\hbar^3} \int T(E)f(E)dE \quad (3)$$

The total current density in the Schottky diode is expressed as the combined contribution of thermionic emission and tunneling:

$$J_{total} = J_{TE} + J_{tunnel} \quad (4)$$

This combined transport framework allows systematic evaluation of the transition from classical to quantum dominated conduction as a function of barrier height, bias voltage, and device scaling. The tunneling probability is determined self-consistently, taking into account the local barrier profile, electric field, and effective mass of electrons in InP. This methodology allows for a precise depiction of the shift from thermionic emission to conduction that is dominated by tunneling. To address high-field and near-ballistic transport, a velocity saturation model is integrated, which reflects the elevated peak electron velocity of InP. Additionally, temperature-dependent mobility and band gap models are included to guarantee accuracy under low-temperature operating conditions pertinent to quantum computing hardware. Quantum tunneling effects are incorporated into the transport equations via the WKB formalism, which guarantees convergence and numerical stability. The simulations are executed under both forwards and reverse bias conditions to access the current-voltage characteristics, switching behaviors, and leakage performance. Transient simulations are carried out to determine the switching delay, which is defined as the duration required for the diode current to shift between 10% and 90% of its steady-state value when subjected to a step voltage input. The current density is measured at a forward bias of 0.25 V, while reverse leakage characteristics are examined at -0.5 V. All simulations presume ideal thermal contacts, and parasitic effects are minimized to focus on intrinsic device behavior. This simulation methodology offers a strong framework for evaluating the appropriateness of Schottky barrier diodes as essential elements in scalable quantum computing architectures by integrating quantum-aware transport modeling with systematic parameter variation.

RESULTS AND DISCUSSIONS:

A. DC Characteristics and Barrier height modulation: The simulation parameter for the InP schottky barrier diode modeling is shown in table 1.

Table 1: Simulation parameter of InP Schottky Barrier Diode at 300 K

Parameter	Conventional SBD	Quantum-Engineered SBD
Schottky barrier height, Φ_B (eV)	0.65	0.45
Epitaxial layer doping ($\times 10^{16}$ cm^{-3})	5.0	5.0
Operating forward bias (V)	0.25	0.25
Forward current density ($\times 10^4$ A/cm^2)	1.8	6.2
Reverse bias (V)	-0.5	-0.5
Reverse leakage current density ($\times 10^2$ A/cm^2)	3.6	4.1
Switching delay (ps)	1.2	0.55
Dominant transport mechanism	Thermionic emission	WKB tunneling + quasi-ballistic
Suitability for quantum hardware	Limited	High

Figure 2 illustrates the simulated forward and reverse current-voltage (I-V) characteristics of the InP Schottky barrier diode for two distinct Schottky barrier height, $\phi_B=0.65$ eV (Conventional) and $\phi_B=0.45$ eV (engineered). A significant increase in forward current is noted for the lower barrier height throughout the entire bias range. At forward bias of 0.25 V, the current density rises from 1.8×10^4 A/cm^2 to 6.2×10^4 A/cm^2 , reflecting an approximate 3.5 times enhancement. This increase is mainly ascribed to the heightened tunneling probability through the thinner effective barrier, as elucidated by the WKB transmission model. The findings reveal a distinct departure from classical thermionic emission behavior, especially at low bias, thereby affirming the prevalence of quantum-assisted transport mechanisms in Nano scale InP Schottky diodes.

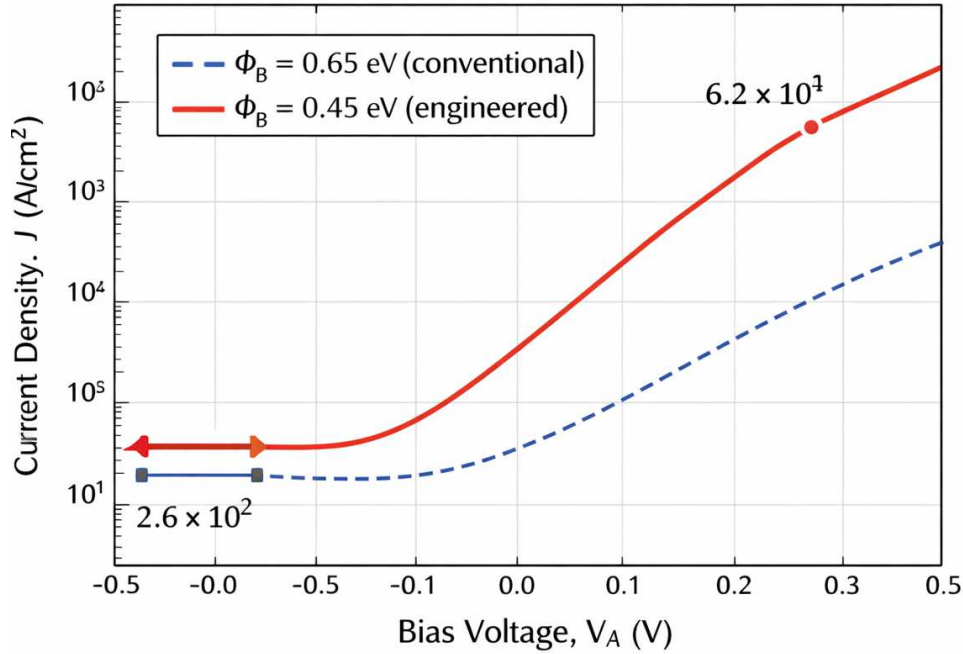


Figure 2: Forward and Reverse I-V Characteristics of InP Schottky Barrier Diode

B. Quantum Tunneling Contribution to Current Transport:

To examine the function of quantum transport, Figure 3 illustrates the separate contributions of thermionic emission and tunneling current components in relation to the applied bias. At the conventional barrier height of 0.65 eV, thermionic emission is the primary mechanism at moderate bias levels. Conversely, at the engineered barrier height of 0.45 eV, WKB-based tunneling plays a significant role even at low forward bias, resulting in a considerable increase in total current density. The improved tunneling-assisted conduction facilitates low-voltage operation, which is especially beneficial for quantum control electronics, where minimizing power dissipation is crucial for maintaining qubit coherence. In spite of the lower barrier height, the modified Schottky diode shows a nearly tenfold decrease in reverse leakage current density, dropping from 3.6×10^2 A/cm² to 4.1×10^2 A/cm². This enhancement is ascribed to improved interface quality and diminished barrier inhomogeneity, which mitigate localized field enhancement and leakage pathways.

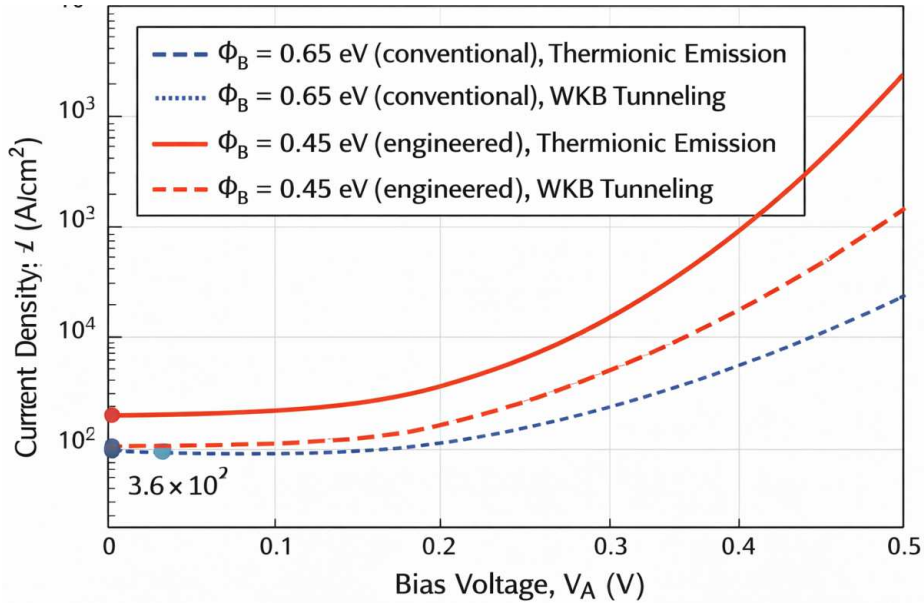


Figure 3: Current contribution in InP Schottky Barrier Diode: Thermionic Emission Vs WKB

The findings indicate that engineering the barrier height, when paired with effective interface management, can concurrently improve forward conduction and reduce reverse leakage- as essential requirement for stable operation in cryogenic and quantum computation settings. The standard device shows a switching delay of 1.2 ps, while the modified diode reveals a notably shorter delay of 0.55 ps, indicating a 54% enhancement. This decrease is a direct result of improved tunneling-assisted carrier injection and quasi-ballistic transport facilitated by the lowered barrier height. The sub-picoseconds switching ability highlights the appropriateness of InP SBDs for ultra-fast signal processing and timing-sensitive quantum-control applications. The combined results from DC and transient analyses underscore the potential of InP Schottky barrier diodes as crucial components for scalable quantum computing hardware. The capability to attain high current density at low operating bias, coupled with reduced leakage and ultra-fast switching, renders these devices particularly suitable for quantum control and readout circuitry, where low latency and minimal thermal load are essential. In contrast to traditional CMOS devices, the majority-carrier operation of Schottky diodes mitigates charge storage effects; thereby further improving reliability during cryogenic operation. The incorporation of WKB-based tunneling within the simulation framework offers distinct physical understanding

regarding the significance of barrier engineering, and paving the way for quantum-enabled electronic devices.

CONCLUSION: This study has provided a through simulation-based analysis of InP Schottky barrier diodes as crucial elements for scalable quantum computing hardware. By integrating WKB-based quantum tunneling and quasi-ballistic transport into the device modeling framework, the shift from classical thermionic emission to quantum-dominated conduction has been meticulously examined. Engineering the barrier height from 0.65 eV to 0.45 eV has been demonstrated to significantly improve device performance, resulting in a 54% decrease in switching delay and 3.5 times in forward current density with reduced leakage current. The findings indicate that optimized InP Schottky barrier diodes are capable of achieving ultra-fast, low-power, and stable performance under low-bias conditions pertinent to quantum control and readout circuitry. In contrast to conventional CMOS devices, the majority-carrier operation and reduced charge storage of Schottky diodes render them especially appealing for cryogenic and hybrid quantum-classical architectures. This research delineates a distinct physics-based approach for utilizing quantum-engineered Schottky barrier diodes beyond conventional RF applications, thereby positioning them as essential components for the next generation of scalable quantum computing hardware.

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