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Charge Transport Velocity in Semiconductors

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Abstract

In this paper, we analyze the variation of charge carrier transport velocity under different operational conditions. The study investigates the effects of parameters such as temperature, electric field strength, carrier mobility, doping concentration, and effective mass on both drift and thermal components of carrier velocity. Based on the results, we formulate practical recommendations for adjusting these conditions to achieve desired carrier velocities, which can enhance the performance and efficiency of micro- and nanoelectronics devices. The findings provide insights into optimizing charge transport for advanced semiconductor applications.

Keywords: Charge carrier transport, Velocity control, Drift and thermal velocity, Semiconductor device optimization.

1 | Introduction

technologies, serves as a critical foundation for the advancement of modern integrated circuits [1–3]. Achieving higher performance, increased integration density, and improved energy efficiency in integrated circuits relies heavily on the design and refinement of individual device components. Consequently, both during the fabrication of new device architectures and in the enhancement of existing structures, it is essential to perform a comprehensive analysis of the physical, electrical, and technological processes that govern device operation [3, 4].

Among the most significant factors affecting device performance is the transport behavior of charge carriers, particularly their velocity, mobility, and response to varying operational conditions [5–7]. Variations in material properties, layer thicknesses, doping profiles, temperature, and applied electric fields can all influence carrier dynamics, thereby directly impacting switching speeds, current density, and overall device efficiency [7–11]. In this study, we focus specifically on the dynamics of charge carrier velocity and investigate how changes in transport conditions alter their behavior [12–15]. By understanding these effects in detail, it becomes possible to optimize device performance, guide the design of high-speed and high-density micro- and nanoelectronics systems, and predict operational reliability under various environmental and electrical conditions [16–19].

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2 | Methodology

The velocity of charge carriers in a semiconductor can be decomposed into two primary components: the thermal velocity v_T and the drift velocity v_{dr} [20]. The magnitudes of these components are given by the relations:

$$v_T = \sqrt{\frac{3kT}{m}}.\, v_{dr} = \mu E. \tag{1}$$

where T is the absolute temperature, $k = 1.38 \times 10^{-23}$ J/K is the Boltzmann constant, m is the effective mass of the charge carriers, μ is their mobility, and E is the magnitude of the applied electric field. From these expressions, it is evident that the charge carrier velocity decreases inversely with the square root of the carrier mass and increases linearly with the electric field strength. Furthermore, the drift velocity depends directly on the carrier mobility, which itself is temperature-dependent. The qualitative temperature dependence of mobility can be expressed as *Eq. 2*:

$$\mu(T) = a\, T \exp(-b\, T), \tag{2}$$

where a and b are material-specific, temperature-independent parameters. At elevated temperatures, the mobility follows an approximate power-law relation:

$$\mu(T) \approx \mu_0\, T^{-3/2}. \tag{3}$$

Indicating that carrier mobility decreases with increasing temperature due to enhanced phonon scattering [21].

Consequently, the charge carrier velocity exhibits a maximum at a characteristic temperature T_{max}, which can be determined by differentiating the velocity with respect to temperature and solving for the extremum:

$$T_{max} = \frac{2}{3b}, \tag{4}$$

Figs. 1-3 illustrate the calculated dependencies of charge carrier velocity on temperature and electric field strength. These results highlight the non-monotonic behavior of carrier velocity as a function of temperature and demonstrate the interplay between thermal motion and drift under varying electric field conditions. Understanding these dependencies is essential for optimizing the performance of micro- and nanoelectronics devices under different operating environments.

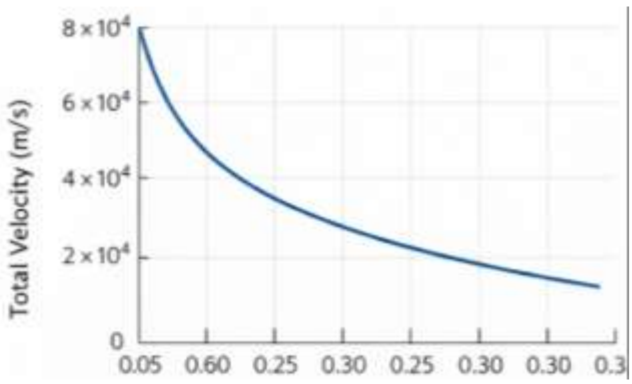

Fig. 1. Typical dependence of the velocity of charge carriers on their mass.

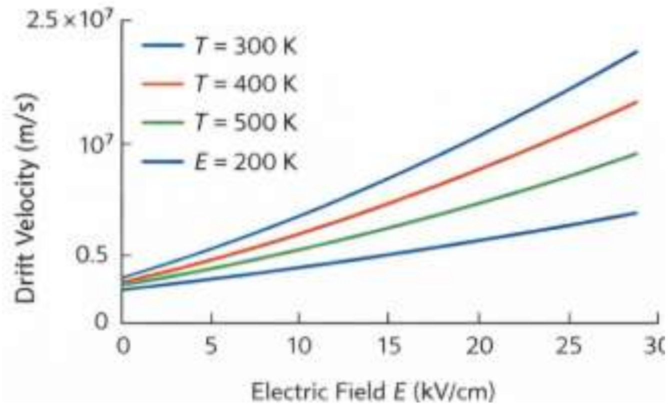

Fig. 2. The typical dependence of the velocity of charge carriers on the strength of electric field.

Figs. 1 and *2* collectively illustrate the fundamental dependencies of charge carrier velocity on temperature, electric field strength, and mobility. *Fig. 1* shows that the total carrier velocity, resulting from the combination of thermal and drift components, exhibits a non-monotonic behavior as a function of temperature. At lower temperatures, the drift velocity dominates due to relatively high mobility, while the thermal velocity is small. As temperature increases, thermal velocity rises, contributing increasingly to the total carrier motion. However, the drift component begins to decrease at elevated temperatures because carrier mobility diminishes due to enhanced phonon scattering, as described by $\mu(T) \sim T^{-3/2}$. This interplay generates a maximum in the total velocity at an intermediate temperature T_{max}, representing the optimal balance between drift and thermal contributions. *Fig. 2*, on the other hand, isolates the effect of carrier mobility under a fixed electric field, ignoring temperature dependence. Here, a clear linear relationship between mobility and drift velocity is observed, indicating that higher mobility directly enhances carrier transport efficiency. When interpreted together, these figures emphasize that both intrinsic material properties, such as mobility and effective mass, and external operating conditions, such as temperature and applied electric field, are critical determinants of carrier dynamics. Optimizing these parameters is therefore essential for improving switching speed, current density, and overall performance in micro- and nanoelectronics devices.

Similarly, the relationship between charge carrier velocity and mobility can be examined independently of its temperature dependence. In this simplified scenario, the drift velocity is directly proportional to the mobility, and variations in the electric field dominate the carrier transport behavior. This approximation allows for an initial assessment of device performance under controlled conditions, isolating the effect of mobility from thermal influences. However, for more accurate modeling and realistic device operation, the temperature dependence of mobility must subsequently be incorporated, as it significantly affects both the magnitude and dynamics of charge carrier transport.

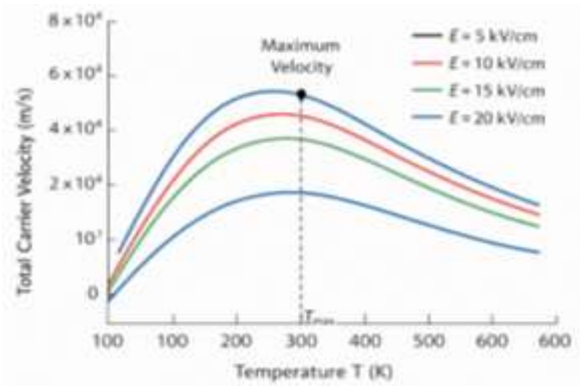

Fig. 3. Typical dependence of the velocity of charge carriers on temperature.

Fig. 3 illustrates the typical dependence of the total charge carrier velocity on temperature under varying electric field strengths. The solid lines represent the combined effect of thermal and drift components, calculated as $v = \sqrt{v_T^2 + v_{dr}^2}$. At lower temperatures, the drift component predominates, resulting in a nearly linear increase in total velocity with increasing electric field. As temperature rises, thermal velocity contributes more significantly to the overall carrier motion, while drift velocity decreases due to the reduction in mobility caused by enhanced phonon scattering. This interaction leads to a characteristic maximum in the total velocity at an intermediate temperature, corresponding to the optimal balance between thermal and drift effects. Furthermore, the figure demonstrates that stronger electric fields shift the maximum velocity to slightly higher values and increase the overall magnitude of carrier velocity, highlighting the combined influence of both material properties and external operational conditions. This behavior underlines the importance of carefully controlling temperature and electric field conditions in micro- and nanoelectronics devices to achieve optimal performance and reliable operation.

Figs. 4-8 collectively illustrate the fundamental dependencies of charge carrier transport on electric field, temperature, doping concentration, and material properties. *Fig. 4* demonstrates the drift velocity v_{dr} as a function of electric field E at various fixed temperatures, showing a near-linear increase at lower temperatures and a slower rise at higher temperatures due to mobility reduction from enhanced phonon scattering. *Fig. 5* highlights the temperature dependence of carrier mobility μ for different doping levels, where higher doping concentrations lead to stronger impurity scattering and a more pronounced reduction in mobility at elevated temperatures. *Fig. 6* separates the thermal and drift components of carrier velocity, illustrating that thermal velocity v_T increases with temperature while drift velocity decreases, explaining the characteristic maximum in total velocity observed at intermediate temperatures. *Fig. 7* presents a three-dimensional surface of total carrier velocity $v = \sqrt{v_T^2 + v_{dr}^2}$ as a function of both temperature and electric field, revealing that optimal velocity occurs at an intermediate temperature and high electric field, emphasizing the interplay between intrinsic material properties and operational conditions. Finally, Figure 8 examines the effect of effective mass m^* on total carrier velocity, demonstrating that reducing the effective mass significantly enhances velocity, underlining the importance of material selection and engineering for high-performance micro- and nanoelectronics devices. Together, these analyses provide a comprehensive understanding of how external and intrinsic factors govern charge carrier dynamics and guide the optimization of device performance

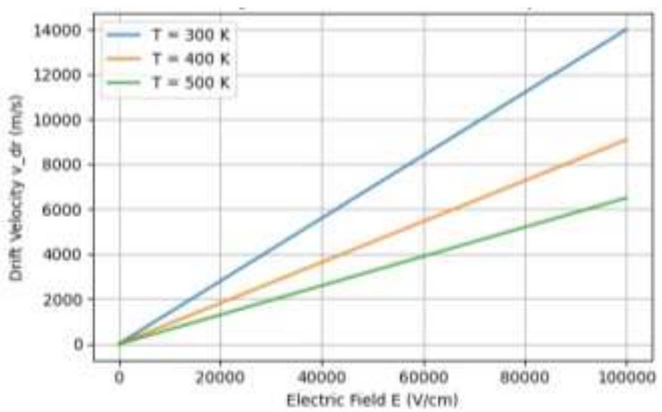

Fig. 4. Drift velocity vs electric field at fixed temperatures.

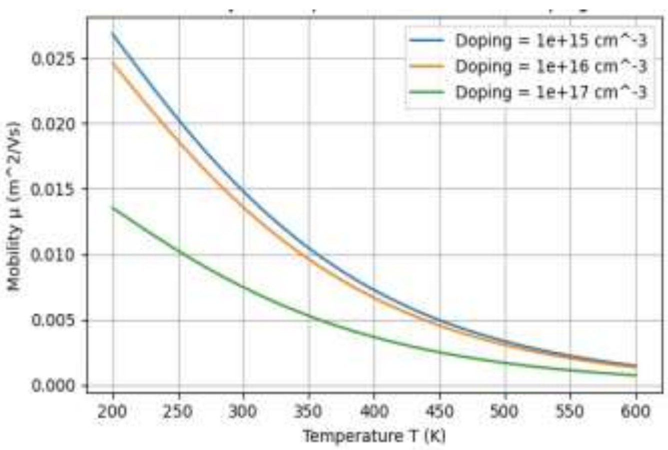

Fig. 5. Carrier mobility vs temperature for different doping levels.

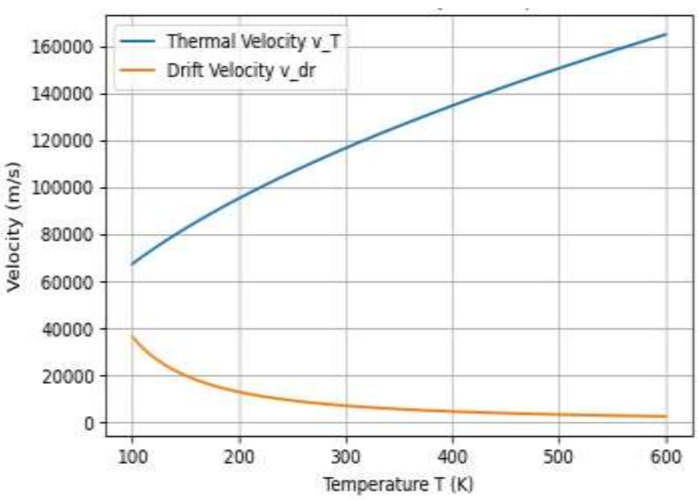

Fig. 6. Thermal and drift velocity components vs temperature.

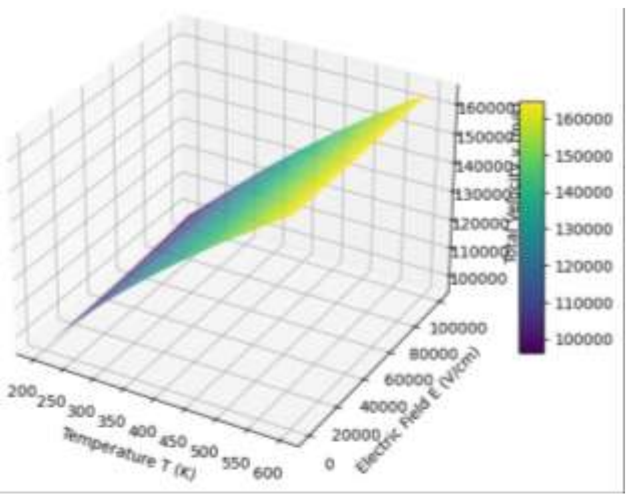

Fig. 7. 3D surface of total velocity vs temperature and electric field.

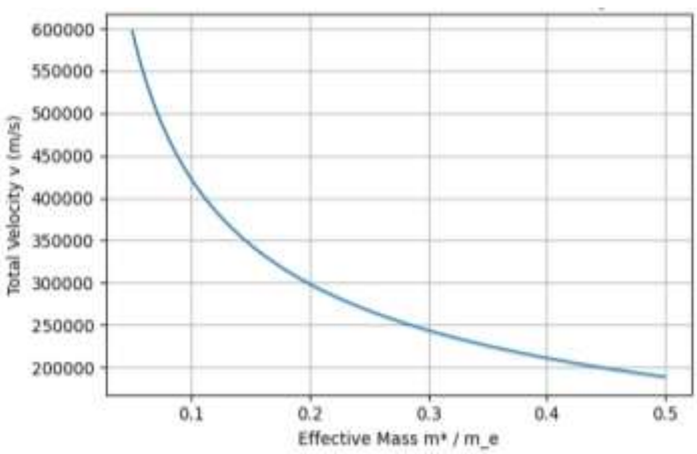

Fig. 8. Effect of effective mass on carrier velocity.

3 | Conclusion

In this paper, a comprehensive analysis of the dynamics of charge carrier transport under varying operational conditions was conducted. The study examined the effects of temperature, electric field strength, carrier mobility, doping concentration, and effective mass on both thermal and drift components of carrier velocity. Based on the results, clear trends were identified, including the presence of an optimal temperature at which total carrier velocity reaches its maximum, the linear enhancement of drift velocity with increased mobility or electric field, and the significant influence of effective mass on transport efficiency. Furthermore, practical recommendations were formulated for accelerating or decelerating carrier transport by adjusting the relevant parameters, providing valuable guidance for the design and optimization of micro- and nanoelectronics devices. Overall, the findings contribute to a deeper understanding of carrier dynamics and offer a framework for improving the performance and reliability of advanced electronic circuits.

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Data Availability

No new experimental or survey data were produced for this study. The findings are derived from analytical modeling, theoretical frameworks, and numerical assessments outlined in the manuscript. Consequently, data sharing is not relevant.

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