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Enhancing Electron Transport in Silicon Self-Switching Devices: A Study on Triangular Barrier-Induced Ballistic Effects

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ABSTRACT

With the increasing demand for high-frequency applications due to congestion in lower frequency bands, the need for high-performance diode detectors has become critical. Achieving fast, efficient, high-frequency response requires diodes with strong rectifying capability and sharp nonlinearity. These electrical characteristics, particularly the I–V behavior of the device, strongly influence key performance metrics such as the curvature coefficient and current responsivity. Derived from the I–V curve shape, these metrics reflect the device's nonlinear behavior. This study investigates how geometrical modifications influence ballistic transport and electrical performance in silicon-based self-switching devices (SSDs). A triangular potential barrier is introduced within the channel to promote ballistic-like electron transport, especially when the channel dimensions are comparable to or smaller than the mean free path (MFP) of charge carriers. Device structures are designed using Silvaco Devedit 3D and simulated in ATLAS. I–V characteristics, hole velocity, and electric field are extracted from Tonyplot. Among the simulated structures, both the fully triangular and the integrated trench designs exhibit substantially higher hole velocities and localised electric fields. Furthermore, the SSD with integrated planar and triangular trenches exhibited a significantly increased forward current, indicating stronger ballistic-like behaviour. This geometry is considered the most promising within the scope of the simulations, with its narrow trench width and short channel length suggesting the possibility of quasi-ballistic or ballistic-like transport. Results further indicate that both the size and shape of the triangular barrier critically affect electrical characteristics, showing their importance for future SSD optimization.

Keywords: *Rectification performance. curvature coefficient, ballistic transport, current response, triangular barrier*

1. INTRODUCTION

Diodes is an electronic device that enables the asymmetric current flow by allowing forward current under forward bias while drastically restricting it under reverse bias [1]. The functionality primarily achieved is based on semiconductor p-n junctions, which take advantage of the inherent electric fields and carrier diffusion processes between different charge carriers. However, the miniaturization of conventional p-n diodes is a significant challenge, such as complex production at the atomic level, tunneling-induced leakage currents, and performance restrictions imposed by doping control and material interfaces [2]. Therefore, this research is carried out to explore alternative rectification processes, particularly those that use quantum and ballistic transport phenomena to produce high-rectification-performance diodes. Geometric diodes represent a paradigm shift, as they manipulate only the motion of carrier charges that exploit ballistic or quasi-ballistic transport in confined, asymmetrically shaped pathways [3]. In addition, they operate like a conventional diode, producing asymmetric I-V characteristics by engineering an asymmetric device shape, functioning in a specific transport regime rather than relying on doping of p-type and n-type materials to create a charge-carrier imbalance [4].

The relationship between the device's geometric dimensions and the Mean Free Path length (MFP) of charge carriers in the material is crucial to the geometrical diode's functionality [5]. The MFP is the average distance a charge carrier, either an electron or a hole, travels between scattering events. When the geometrical shape dimensions of a conductive channel length or channel width are comparable to or smaller than the MFP, ballistic transport takes precedence. Under ballistic conditions, charge carriers are injected from a narrow channel to a wider channel. As they enter the wide region, they can separate freely, which results in high conductance (like forward bias in a normal diode). In contrast, charge carriers injected from the wide channel into the small channel will experience constriction. Many carriers collide with the tapering walls and are reflected or scattered before reaching the narrow neck, resulting in much decreased conductance (like reverse bias). An asymmetric structure will aid the rectification by influencing directional transmission, but the device still requires a certain type of doping to control channel conduction. Doping plays the key factor in opening and closing the channel, enabling switching behavior that geometric design alone cannot achieve, especially under non-ideal or non-ballistic transport conditions where scattering becomes significant.

Several diode devices have been introduced using the concept of ballistic transport, such as the Self-Switching Diode (SSD) [6, 7], the geometrical diode, the Planar Barrier Diode (PBD) [8], and a hybrid of PBD and SSD [9]. In addition, both SSD and PBD have been implemented in many applications such as frequency detector [10, 11], full-wave bridge rectifier [12 - 14], thermoelectric rectifier [15] and microwave rectifier [8, 16].

This study explores self-switching diodes (SSDs) by introducing a new triangular trench design. Alongside the traditional rectangular trench, the triangular geometry is examined to determine its effects on carrier transport. By comparing the electrical characteristics of holes in both trench types, the research aims to determine whether the devices show ballistic-like behavior. If ballistic transport can be achieved in the channel, it could lead to improved carrier mobility and enhanced electrical performance, such as greater current response and better rectification efficiency.

2. MATERIALS AND METHODOLOGY

Prior to the proposed structural modification of the SSD, the baseline parameters were adapted from the work of Yi Liang et. al. (2022), as shown in Figure 1. This reference structure featured a channel length, L, channel width, W, and channel trench, W_t, of 1.30 μm, 0.23 μm and 0.10 μm, respectively [11]. This geometry was implemented in the Silvaco Devedit 3D and subsequently simulated using ATLAS Silvaco. The SSD was constructed SSD on a p-type silicon substrate with a doping concentration of 2.45×10^{16} cm^{-3}, with an interface charge density of 3.16×10^{11} cm^{-2} applied along the channel [7, 11]. To accurately model and emulate the electron-transfer mechanism of the real device, physical models such as Klaassen's unified low-field mobility model, the Watt model, Auger recombination, and the energy-balance transport model were incorporated [7, 11, 17]. In this study, we employed advanced physical models, including the energy balance transport model, to examine the potential for ballistic or quasi-ballistic transport in SSD structures. We don't know exactly how the fabricated device will transport electrons, but these models will help us examine how carriers will behave in situations where ballistic transport is likely. This method gives us useful information on how to develop and improve nanoscale device designs that want to improve current response by reducing scattering.

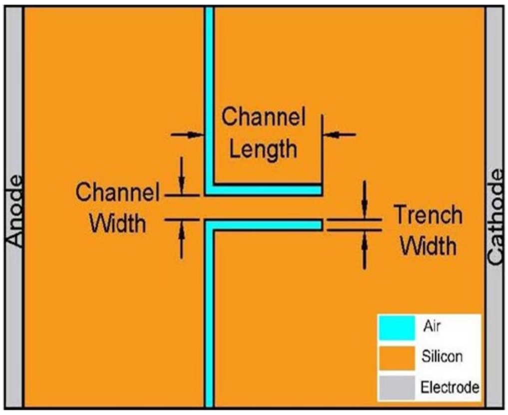


Figure 1. The structure of SSD has been selected for different geometrical shape changes.

2.1. Different Structure of A Geometrical Diode

In this section, two additional geometrical modifications to the SSD structure are proposed, both incorporating triangular-shaped insulating regions to introduce engineered potential barriers within the channel. As illustrated in Figure 2(a), the first design integrates a combination of planar and triangular trench geometries, aiming to leverage the benefits of both gradual carrier injection and localized electric field enhancement. The second design, shown in Figure 2(b), features a fully triangular trench structure, intended to maximise field concentration and carrier acceleration through a sharp constriction.

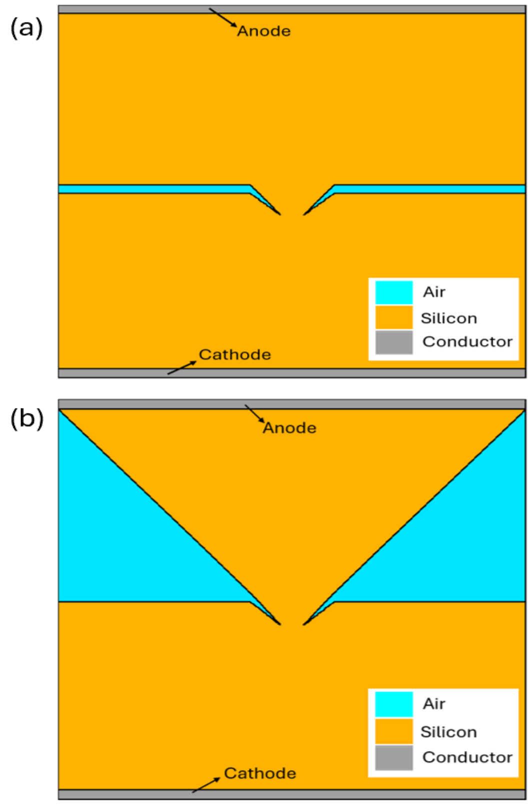


Figure 2. SSD (a) with integration of planar and triangular trench, and (b) with fully triangular barrier structure.

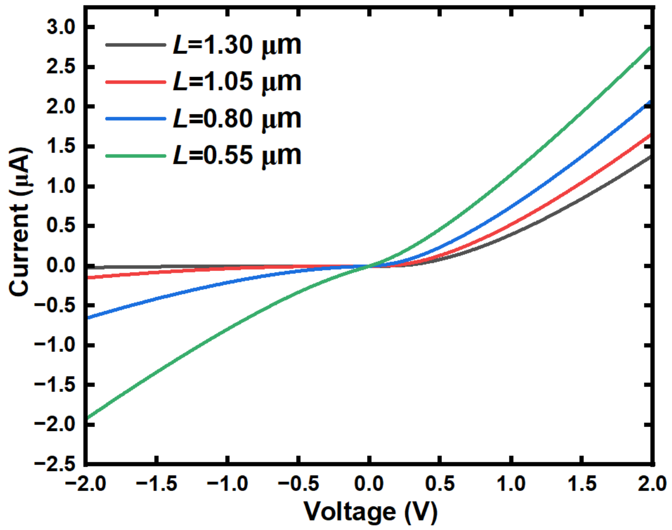
These modifications are introduced to investigate their effects on carrier transport characteristics and to assess the potential for promoting ballistic-like behavior in the channel.

3. RESULTS AND DISCUSSION

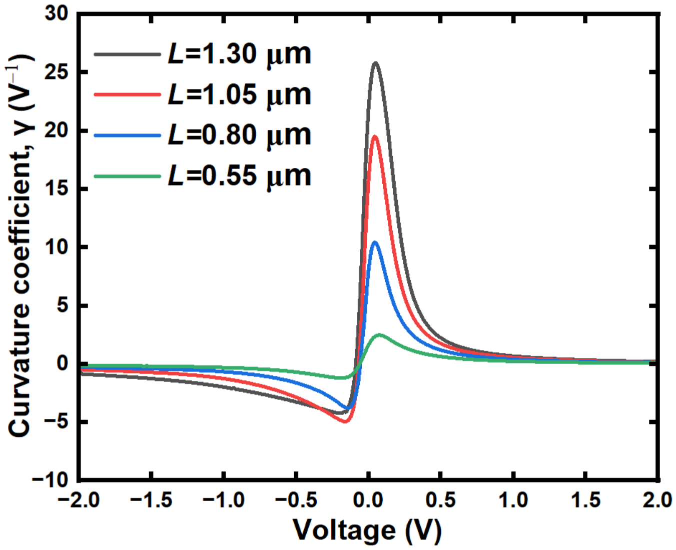
3.1. Planar Trench

Two planar trench SSD structures with different channel lengths were designed to investigate the impact of channel scaling on device performance. We observed the current-voltage (I-V) characteristics shown in Figure 3(a) by applying a positive bias to the anode and a negative bias to the cathode. The results show that devices with shorter channel lengths have much higher forward current. This means carriers have lower dispersion and resistance, making them easier to move. But this benefit is canceled out by the fact that the leakage current goes up when the bias is reversed. This is probably because the electrostatic control is weaker and the tunneling or thermionic emission effects are stronger in the shorter channel. Figure 3(b) shows the curvature coefficient analysis, indicating that a channel length of 0.55 µm does not meet the minimum curvature coefficient requirement of 3.5 V^{-1} for efficient current rectification [18].

The research investigates the hole velocity, hole temperature, and electric field profiles in two planar trench SSDs with varying channel lengths to enhance the comprehension of carrier transport mechanisms. Figures 4 through 6 show all of the results. Figures 4 and 5 show that the hole velocity is low at the channel entrance but increases rapidly toward the exit. This means that holes speed up as they move through the channel [19, 20]. This trend matches the electric field distribution in Figure 6, which shows that stronger electric fields near the channel exit lead to faster hole speeds. [21, 22]. Importantly, in devices with shorter channels, holes exit the channel more quickly, suggesting reduced dispersion and a shorter transit time. In contrast, holes traveling through the longer channel experience more frequent interactions, requiring a larger number of carriers to transfer momentum and accelerate. This results in a decrease in hole temperatures, as shown in Figure 5 [23]. These observations collectively suggest that ballistic or quasi-ballistic transport is more prominent in the shorter-channel device, though evidence of such transport mechanisms is also observed in the longer-channel device under high-field conditions.



(a)



(b)

Figure 3. (a) I-V characteristic (b) curvature coefficient, γ of channel length, L from 0.55 μm to 1.3 μm.

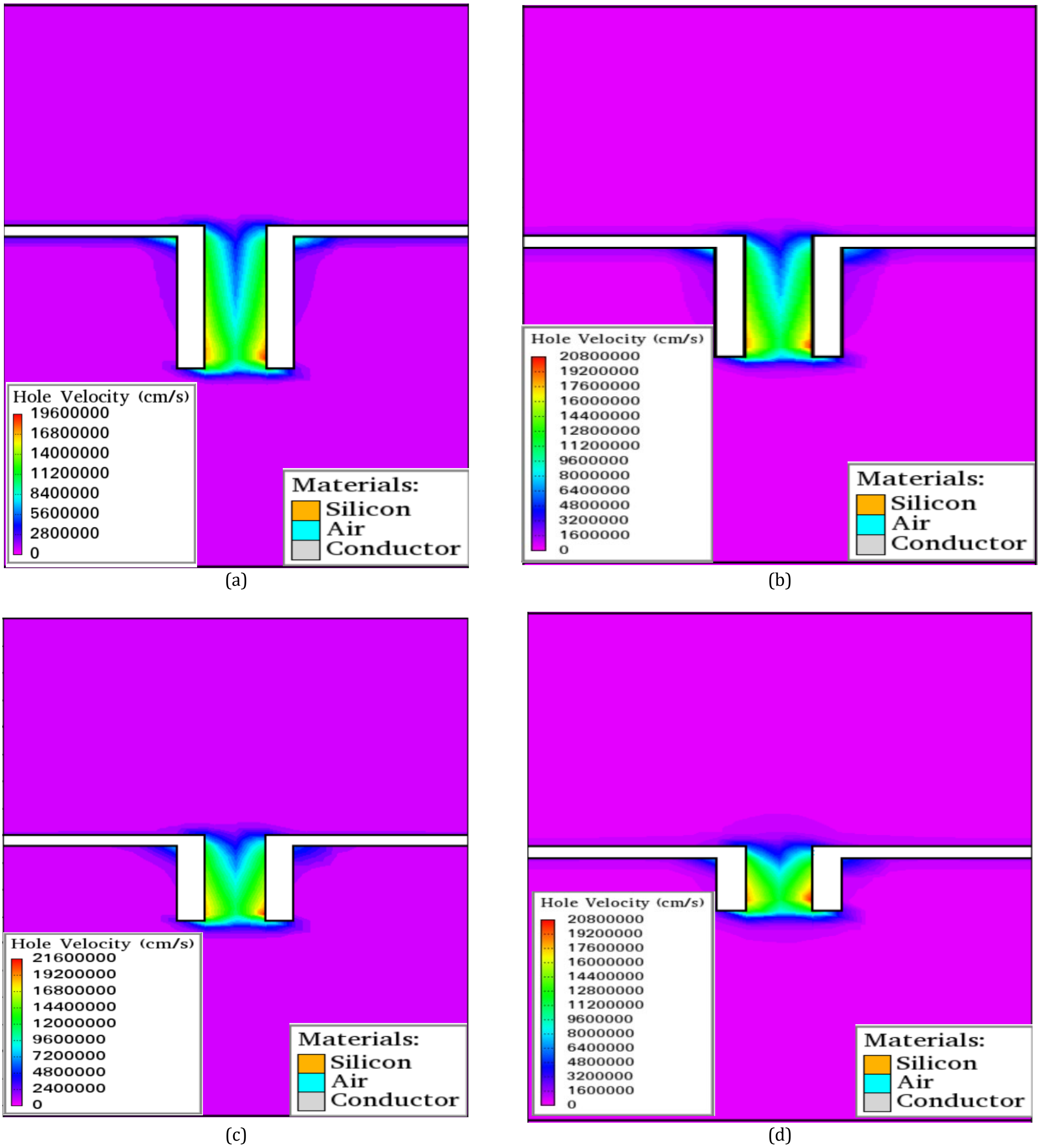
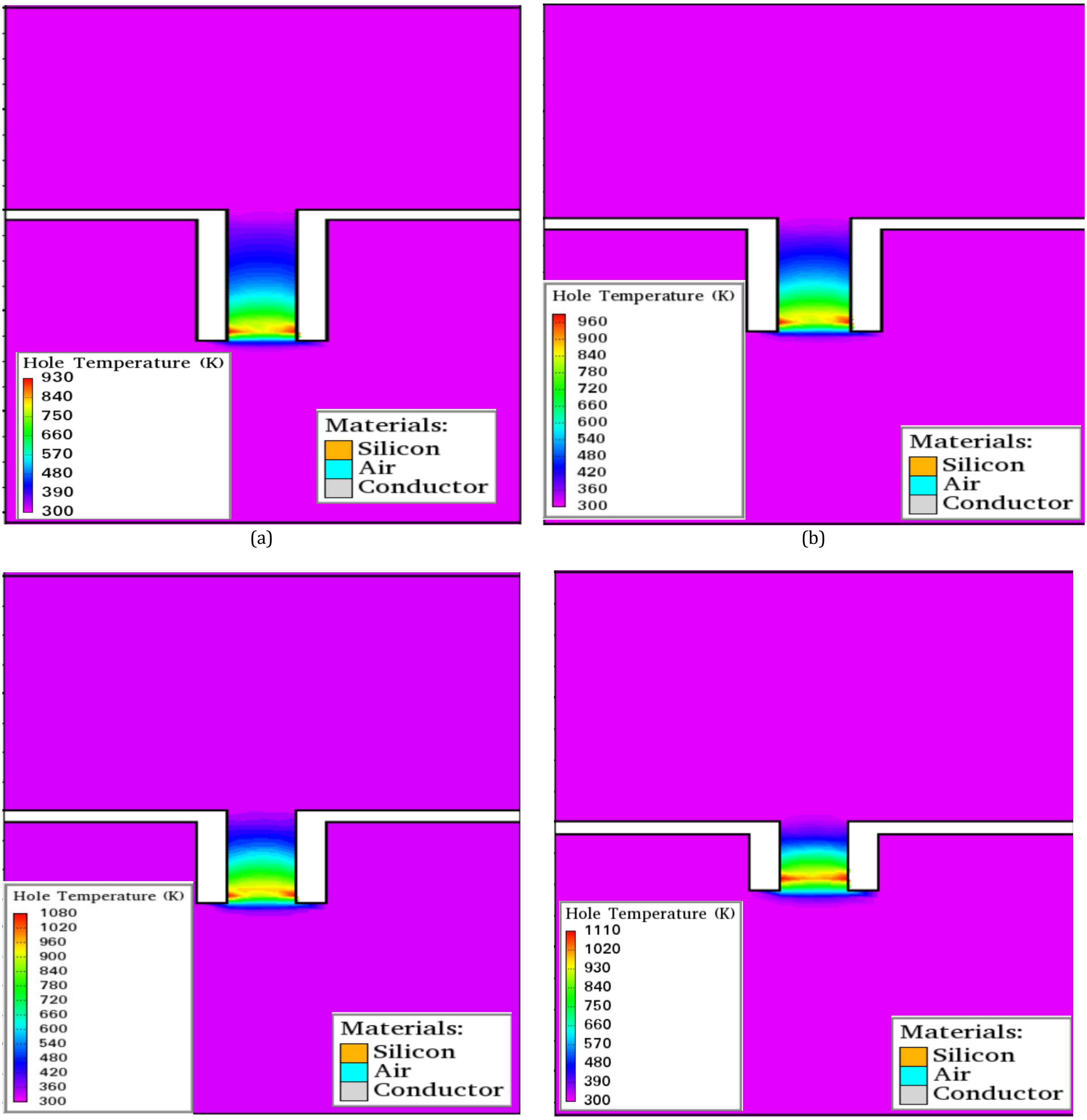


Figure 4. Hole velocity of the SSD with channel length, *L* (a) 1.3 µm, (b) 1.05 µm, (c) 0.80 µm, (d) 0.55 µm.



(a) (b) (c) (d)

Figure 5. Hole temperature of the SSD with channel length, *L* (a) 1.3 µm, (b) 1.05 µm, (c) 0.80 µm, (d) 0.55 µm.

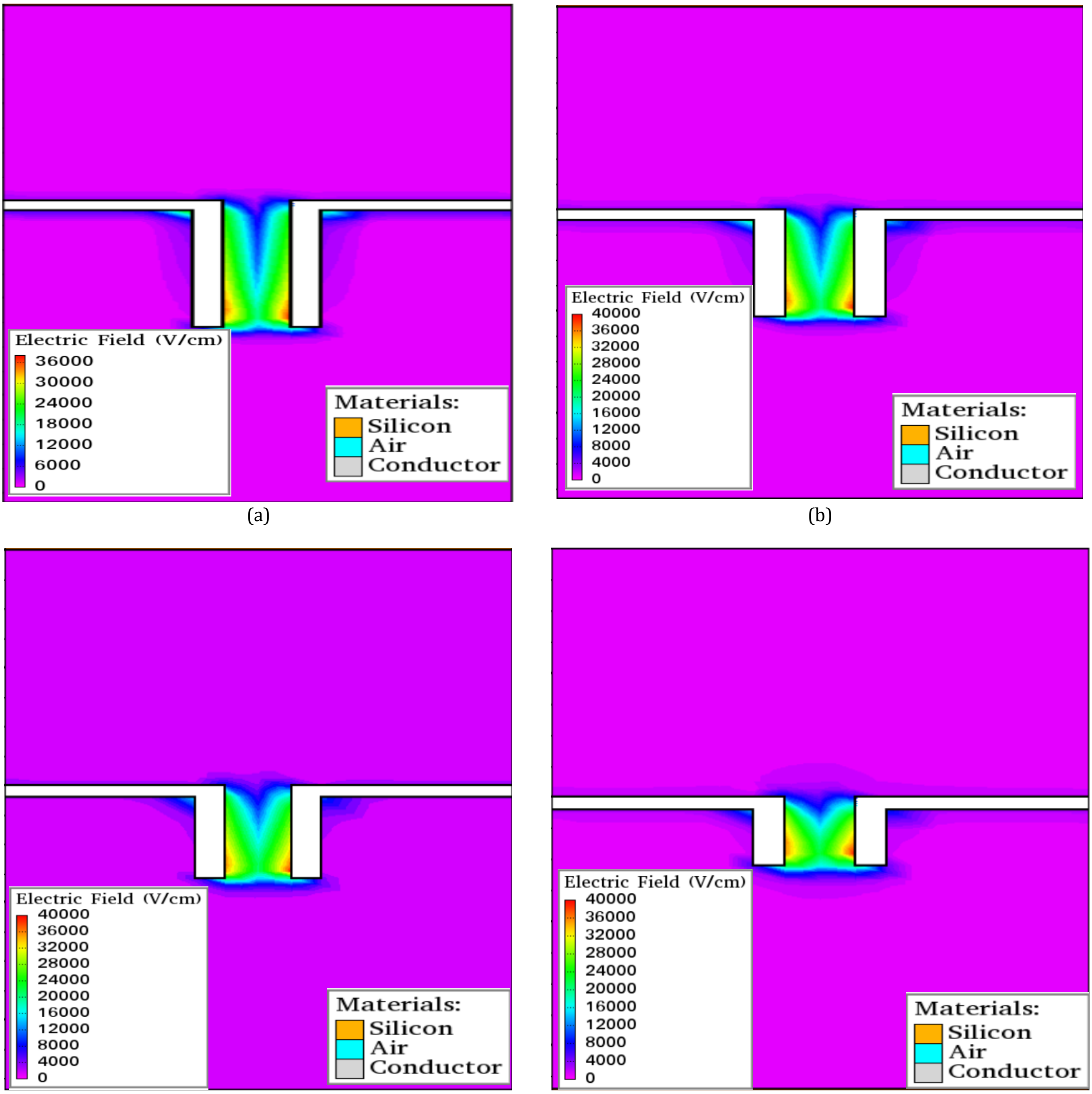


Figure 6. Electric field distribution of the SSD with channel length, *L* (a) 1.3 μm, (b) 1.05 μm, (c) 0.80 μm, (d) 0.55 μm.

3.2. Fully Triangular Barrier Structure

Figure 7 (a) shows the I–V characteristics of the fully triangular barrier structure. The results indicate a significantly higher forward current than the planar trench design, suggesting enhanced carrier transport efficiency. The minimum curvature coefficient of this structure was observed to be above 3.5 V^{-1}, as shown in Figure 7(b), which motivated us to conduct a detailed electrical property analysis of the fully triangular structure. As shown in Figure 8(a), the triangular barrier structure exhibits a higher hole velocity than the planar trench. The high hole velocity is due to a strong localised electric field within the triangular region, as shown in Figure 8 (b). The intensified field accelerates carriers more rapidly, leading to higher velocities and increased carrier energy. As a result, more frequent hole–hole interactions occur, which appear as elevated hole temperatures near the channel exit, as shown in Figure 8(c). Furthermore, the observed reduction in hole density within the active channel, particularly near the narrow triangular region, supports the hypothesis of ballistic-like transport. In this regime, carriers traverse the confined channel with minimal scattering, maintaining high velocity and energy. This behavior aligns with the purposefully engineered triangular barrier, which was designed to facilitate rapid, low-scattering carrier transport through the channel.

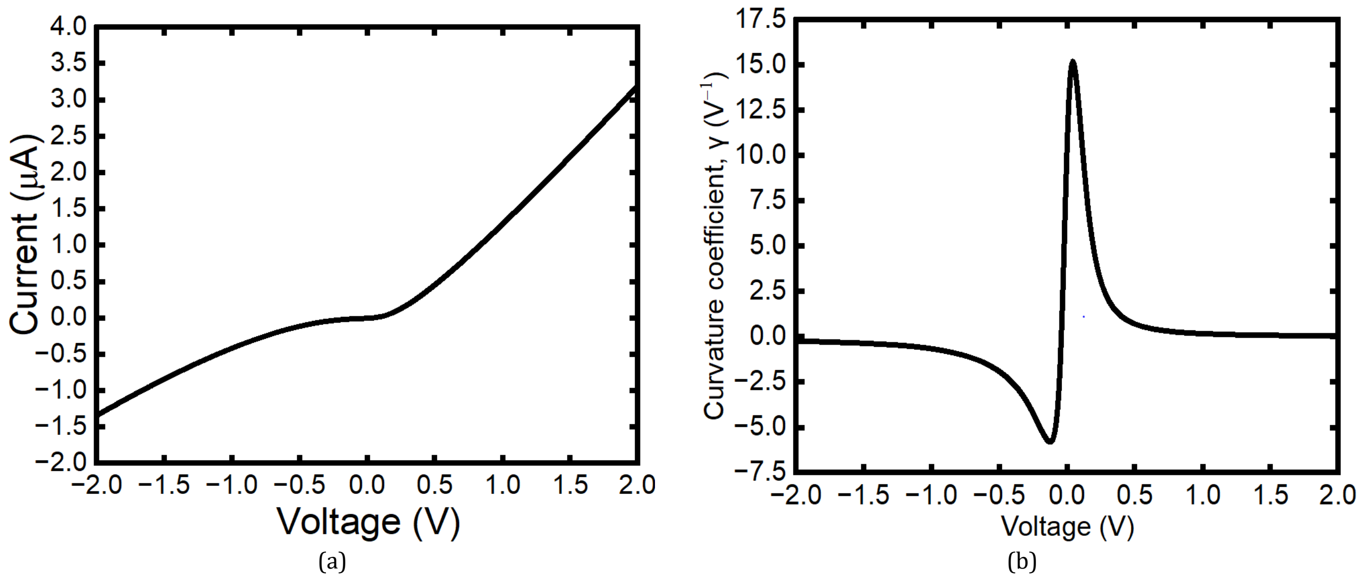


Figure 7. (a) I-V characteristics (b) curvature coefficient of a fully triangular barrier structure.

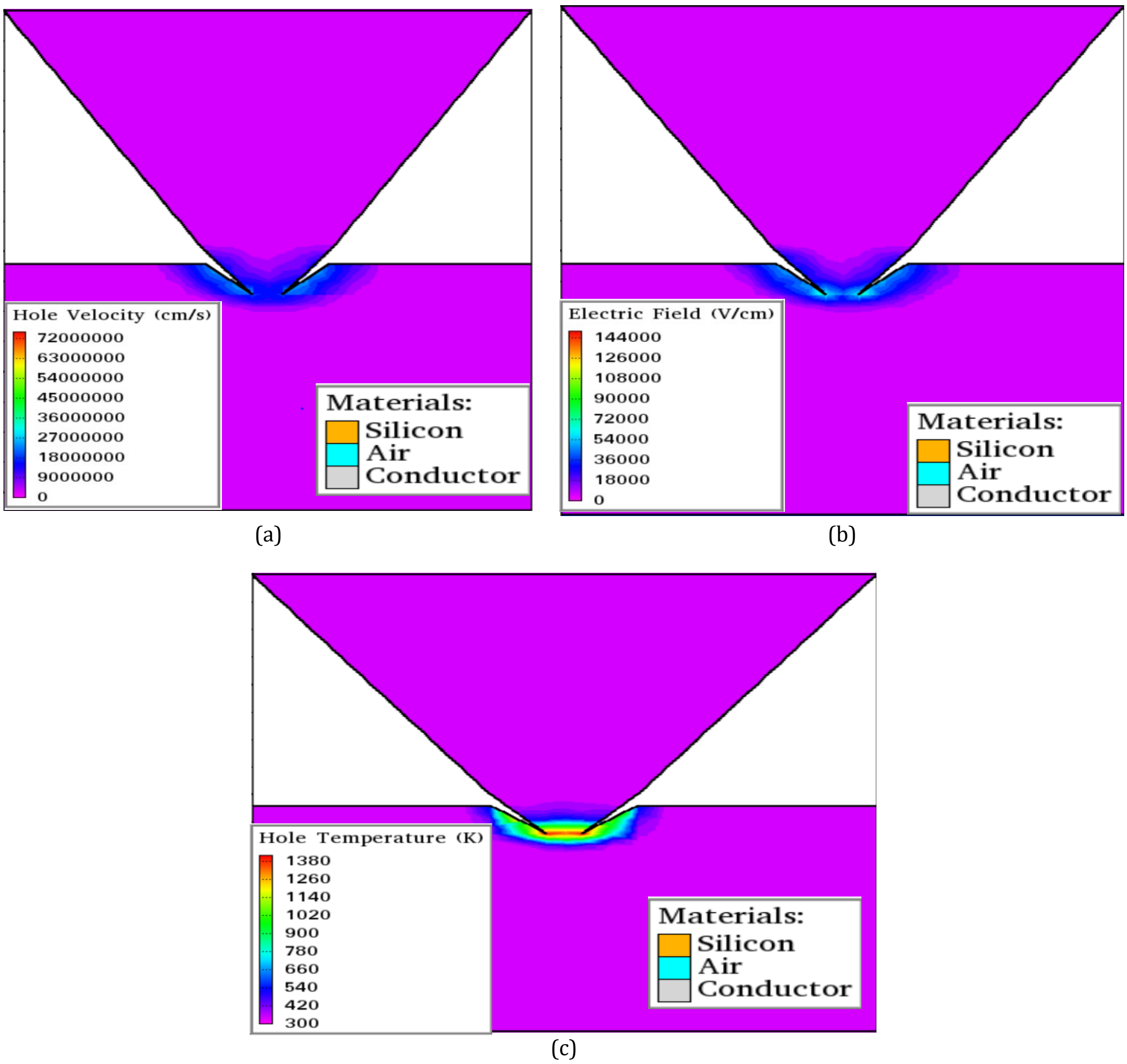
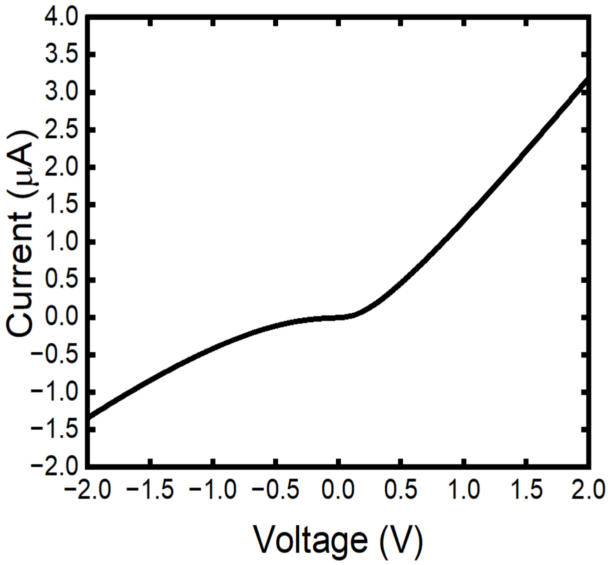


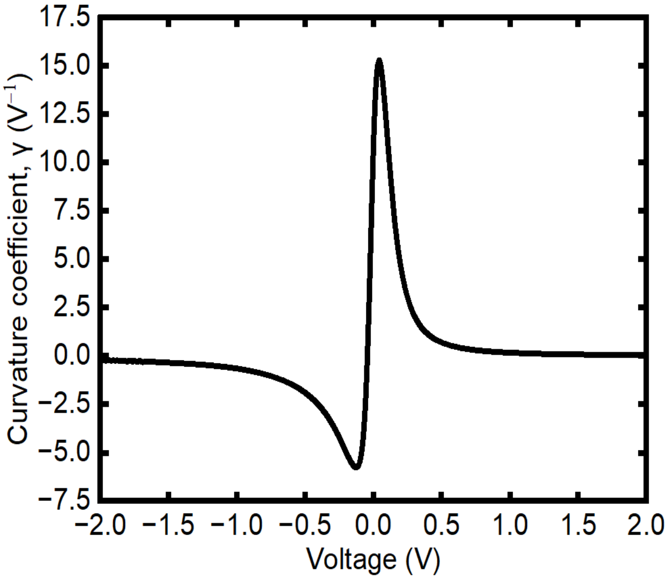
Figure 8. Electrical properties of fully triangular barrier SSD structure: (a) hole velocity (b) electric field, and (c) hole temperature.

3.3. Integration of Planar and Triangular Trench

Figure 9 presents the I–V characteristics and its respective curvature coefficient for the structure integrating both planar and triangular trenches. The results show only minor differences, with slightly better performance in forward currents, reverse currents, and the curvature coefficient compared to the fully triangular barrier structure shown in Figure 7. Although the variation in I–V characteristics is modest, we further investigate its internal electrical properties to understand the cause. As shown in Figure 10(a), the integrated structure demonstrates a significantly higher hole velocity compared to both the fully triangular and planar trench structures. This enhancement is attributed to a stronger localized electric field in the hybrid geometry, particularly where the planar and triangular regions converge, as illustrated in Figure 10(b). At higher velocities, holes are more likely to collide with each other, especially when they travel from different directions. This leads to a rise in hole temperature near the channel exit, as shown in Figure 10(c). The integrated structure exhibits an even lower hole density in the active channel compared to the fully triangular design when we analyze the carrier concentration. This indicates that angled collisions and strong-field effects create conditions such as ballistic transport, in which holes retain high velocity and energy with minimal scattering. Such behavior aligns with the design objective of merging planar stability with triangular acceleration to achieve efficient, low-dispersion carrier transport.



(a)



(b)

Figure 9. (a) I-V characteristics (b) curvature coefficient of an integrating both planar and triangular trenches barrier structure.

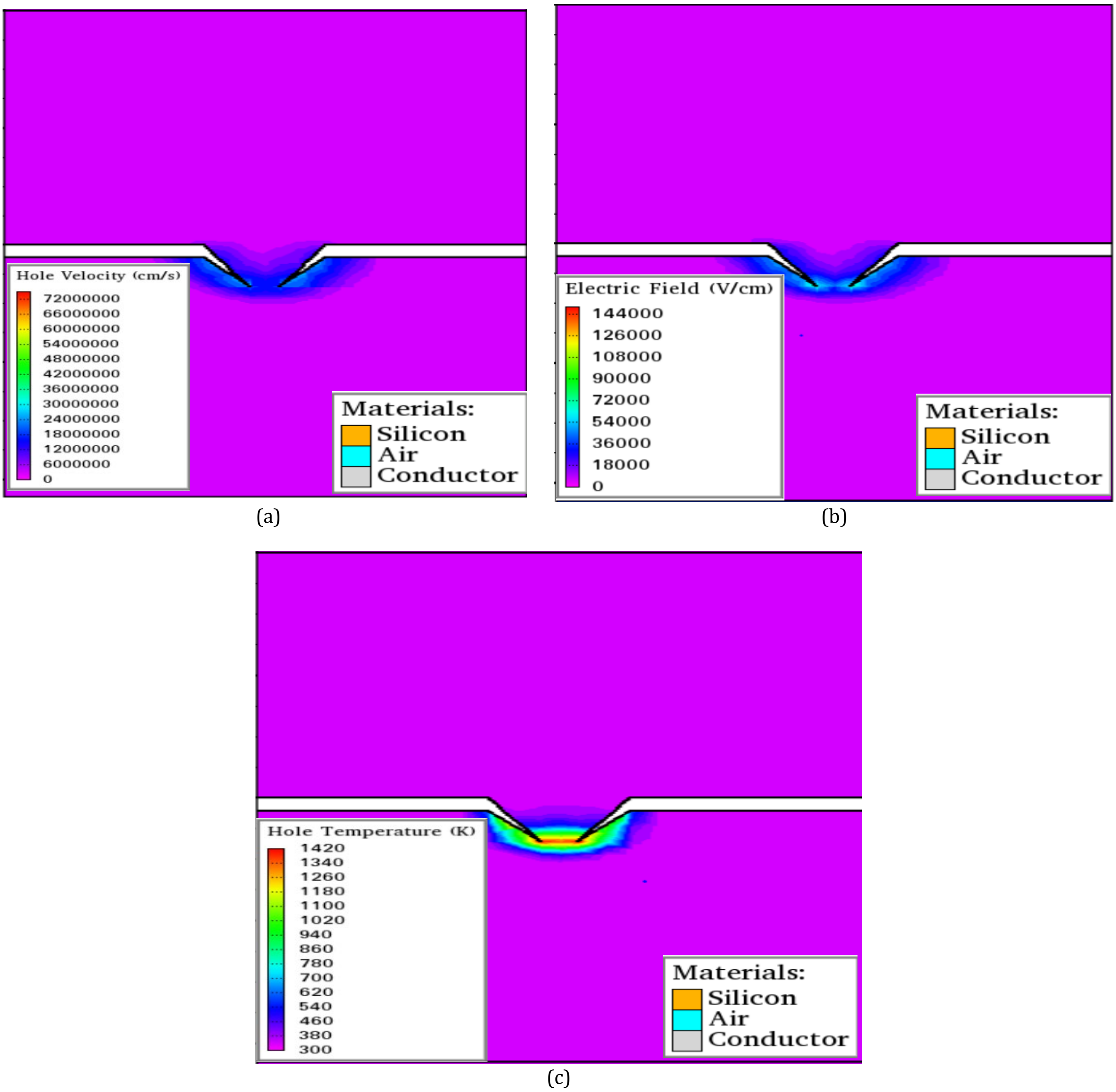


Figure 10. Electrical properties of integrated planar and triangular SSD trench: (a) hole velocity, (b) electric field, and (c) hole temperature.

4. CONCLUSION

In conclusion, this study examined the ballistic and quasi-ballistic phenomena of various SSD topologies, including rectangular trenches, fully triangular barriers, and integrated planar-triangular trenches, to evaluate their impact on carrier transport through simulation. We found that shortening the channel in a rectangular trench increases hole velocity while limiting dispersion, thereby making transport more efficient. The fully triangular and integrated trench structures both showed much higher hole velocities and stronger localized electric fields. This suggests that they behave more like ballistic objects. The integrated structure had the highest forward current and hole velocity of all the geometrical structures. This is probably because the planar region made it easy for carriers to enter, and the triangular barrier made it easy for them to speed up.

The simulations employed advanced physical models in ATLAS Silvaco, including the energy-balance transport model, to investigate the feasibility of ballistic transport. These models were selected to accurately represent non-equilibrium phenomena and short-channel dynamics that traditional drift-diffusion models fail to fully characterize. Even though we don't know exactly how real devices move things around, these models give us a good idea of how ballistic transport might happen in nanoscale structures. It's important to remember that real devices often have a mix of ballistic, diffusive, and thermionic transport processes. These processes can interact, causing current levels to exceed those shown by simulations. The findings of this study indicate that implementing triangular barriers, especially when combined with planar regions, can facilitate high-velocity, low-scattering carrier motion, offering an attractive approach to improving the functionality of self-switching devices.

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