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Research on Multi-Region Compensation Plasma Device

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ABSTRACT: Conventional solid-state plasma devices encounter limitations in terms of the concentration and distribution uniformity of solid-state plasma, which adversely affects their microwave characteristics and overall antenna system performance. In this study, we propose a novel heterogeneous SPIN diode with multi-region compensation effects aimed at addressing this challenge. By incorporating SiGe regions within the intrinsic region of the device, we enhance the carrier injection ratio, effectively compensating for the rapid attenuation of solid-state plasma. As a result, a high-concentration and uniformly distributed solid-state plasma region is achieved within the SPIN diode, surpassing a concentration threshold of $1 \times 10^{18}\,\mathrm{cm}^{-3}$ within the intrinsic region. Through extensive simulations utilizing Sentaurus TCAD software, we demonstrate notable improvements in plasma concentration, distribution uniformity, and other key electrical parameters compared to traditional devices. The presented findings mark significant advancements in the realm of silicon-based plasma devices and hold promise for reconfigurable antenna systems.

1. INTRODUCTION

In recent years, the demand for intelligent and integrated communication systems has increased significantly due to the rapid progress of the aerospace and information industries, as well as evolving social needs [1, 2]. As a critical component in communication systems, antennas play a pivotal role in determining overall system performance. However, traditional metal antennas face limitations such as inflexible design, substantial weight and volume, and inadequate stealth capabilities, rendering them insufficient to meet the ever-growing requirements of modern communication systems [3–6].

To address these challenges and enable enhanced system integration, reconfigurable antennas based on solid-state plasma devices have emerged as a promising solution. These antennas utilize lateral surface PIN (SPIN) diodes as antenna units, replacing metal counterparts, and achieve radiation and reception of electromagnetic waves through the microwave characteristics of the internal solid-state plasma region within the diode [7]. In comparison to traditional metal antennas, solid-state plasma antennas based on the SPIN diodes offer dynamic reconfiguration, stealth capabilities, compatibility with integrated circuit processes, and flexible adjustment of system structure and characteristics.

Nonetheless, the performance of these antennas is directly influenced by the microwave characteristics of the solid-state plasma region within the SPIN diode. In comparison to conventional switch PIN devices, SPIN diode represents a distinct class of lateral semiconductor device. During its operation, an intrinsic region within the diode hosts a solid-state plasma with a carrier concentration surpassing $10^{16}\,\mathrm{cm}^{-3}$. This state manifests "metal-like" characteristics, facilitating effective interaction with external electromagnetic waves and enabling emission and reception of electromagnetic radiation [8, 9]. Nevertheless, constraints concerning carrier injection ratio and mobility introduce challenges, leading to suboptimal and nonuniform distribution of solid-state plasma concentration within the intrinsic region, exhibiting a distinctive "chain-like" pattern. Consequently, this irregular distribution significantly undermines the microwave performance of the SPIN diode [10–14]. Hence, it becomes imperative to investigate novel SPIN diodes featuring high concentrations of solid-state plasma, thereby propelling the advancement of plasma devices and their associated antenna systems.

To overcome this limitation and improve the concentration and distribution uniformity of the solid-state plasma, this study introduces a novel heterogeneous SPIN diode with multi-region compensation effects. The proposed design incorporates regionally compensated heterostructure SiGe regions within the intrinsic region, leading to enhanced carrier injection ratio within the device, improved attenuation of solid-state plasma, and heightened concentration and uniformity of solid-state plasma within the SPIN diode. This advancement serves as a foundation for the development of silicon-based plasma devices and reconfigurable antenna systems [15–19].

This paper is organized as follows. In Section 2, the working mechanism and structural parameters of the SPIN diode are demonstrated. In Section 3, characteristics of the SPIN diode are discussed. Conclusion is given in Section 4.

2. SPIN DIODE

The conventional SPIN diode, as depicted in Fig. 1, comprises heavily doped active regions (P+ and N+), high-resistance silicon intrinsic regions, buried oxide layers, metal contact regions, and high-resistance silicon substrates. When integrating the SPIN diode, a plasma device, with silicon-based antennas,

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FIGURE 1. Conventional SPIN diodewith single channel.

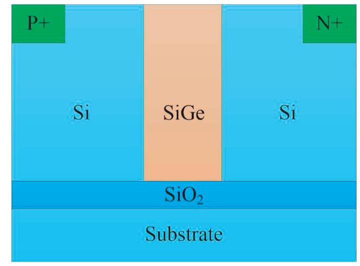

FIGURE 2. Novel SPIN diodewith multi-region compensation.

crucial considerations arise regarding the device's dimensional attributes in relation to solid-state plasma concentration, distribution, and antenna operating frequency. Consequently, the intrinsic region assumes a length not exceeding 200 micrometers, typically demonstrating a depth spanning 2–3 times the skin depth — a characteristic pattern in such scenarios. For instance, when the antenna operates at a frequency of 10 GHz, the intrinsic region's thickness amounts to approximately 80 micrometers. Within this specific context, the presence of carrier scattering, recombination, and lifetime variations exerts discernible influences, resulting in a distinctive "chain-like" distribution of the solid-state plasma within the intrinsic region. Notably, proximity to the intrinsic region's center or bottom corresponds to declining concentrations of the solid-state plasma. As an outcome, the microwave characteristics of both the SPIN diode and its affiliated antenna system undergo pronounced deterioration.

To address this issue and improve the concentration and distribution uniformity of solid-state plasma, we propose a novel heterogeneous SPIN diode with multi-region compensation effects, as displayed in Fig. 2. The device exhibits a fundamental structure akin to the conventional SPIN diode, albeit distinguished by the incorporation of a SiGe region within its intrinsic region. By capitalizing on the differential bandgaps between Si and SiGe materials, the carrier injection ratio within the intrinsic region is augmented to counterbalance the swift decay of solid-state plasma at its central domain. As a result, an elevated and uniformly distributed solid-state plasma region is achieved within the confines of the SPIN diode. The intrinsic region spans a length of 100 micrometers while boasting a depth of 80 micrometers. Notably, the SiGe region located at the center of the intrinsic region extends over a length of 20 micrometers. The introduction of an oxide layer effectively curbs carrier diffusion towards the substrate, thereby confining the solid-state plasma exclusively to the uppermost silicon layer and facilitating additional enhancements to the device's microwave performance.

The on-state current flow in the PIN diode is governed by three current transport mechanisms:

1) At very low-current levels, the current transport is dominated by the recombination process within the space-charge layer of the P-N junction (referred to as the recombination current).
2) At low-current levels, the current transport is dominated by the diffusion of minority carriers injected into the 'i' region (referred to as the diffusion current).
3) At high-current levels, the current transport is dictated by the presence of a high concentration of both holes and electrons in the 'i' region (referred to as the high-level injection current).

The conductivity can be concluded as follows [20]:

$$\sigma = \frac{ne^2 t}{m} \tag{1}$$

Thus, the current density J is shown as:

$$\mathrm{J} = \frac{ne^2 t}{m} E \tag{2}$$

3. CHARACTERISTICS OF THE SPIN DIODE

In this investigation, we delve into the examination of a novel heterogeneous SPIN diode imbued with multi-region compensation effects. The exploration is conducted through the utilization of Sentaurus TCAD, a simulation software widely employed in electronic device research. By conducting meticulous comparisons encompassing crucial aspects such as plasma concentration, distribution uniformity, and various other electrical parameters, we meticulously ascertain the robustness and accuracy of the proposed device design. Throughout the simulation process, the active region of the device showcases a diligently selected doping concentration of $5 \times 10^{20}\ \mathrm{cm}^{-3}$. Furthermore, the intrinsic and substrate regions are constructed using high-resistivity silicon materials, effectively attaining conductivity levels reaching up to 1 S/m. It is essential to note that all obtained results are derived under ambient conditions, precisely at room temperature.

When a forward voltage of 2 V is applied across the terminals of the SPIN diode, the internal carriers in the active region diffuse towards the intrinsic region. At this juncture, the diode operates in a state of high injection, leading to the formation of a high-density solid-state plasma within the intrinsic region. Contrasting with conventional diodes, the distribution curves of solid-state plasma at different positions in the new device are illustrated in Fig. 3. As depicted, for the traditional device, the plasma concentration decreases rapidly at $y = 10\ \mu\mathrm{m}$, dropping from $2 \times 10^{18}\ \mathrm{cm}^{-3}$ to $8 \times 10^{17}\ \mathrm{cm}^{-3}$, exhibiting a concentration difference rate of up to 150% and poor uniformity. Furthermore, the average concentration of solid-state plasma in the intrinsic region of the traditional device remains less than

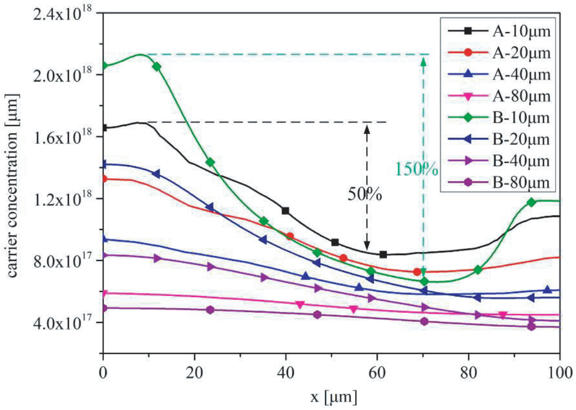

FIGURE 3. Plasma concentration curves (y-direction) of the novel SPIN diode (A) and conventional SPIN diode (B).

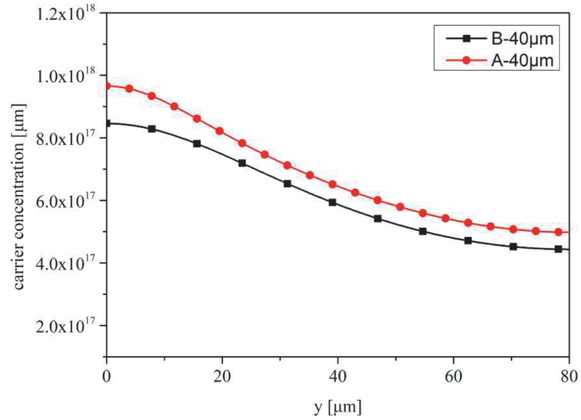

FIGURE 4. Plasma concentration curves (x-direction) of the novel SPIN diode (A) and conventional SPIN diode (B).

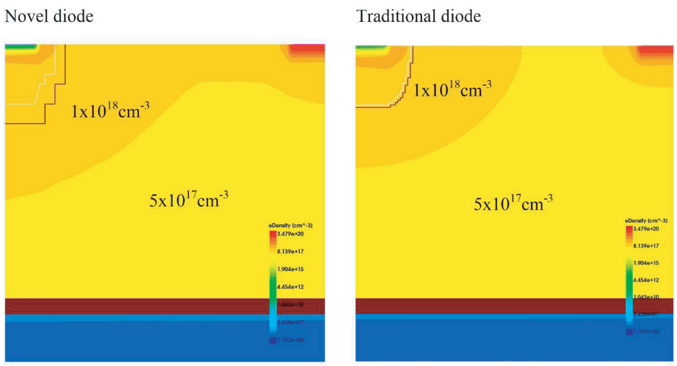

FIGURE 5. Two-dimensional plasma distributionsof both the novel SPIN diode and the traditional device.

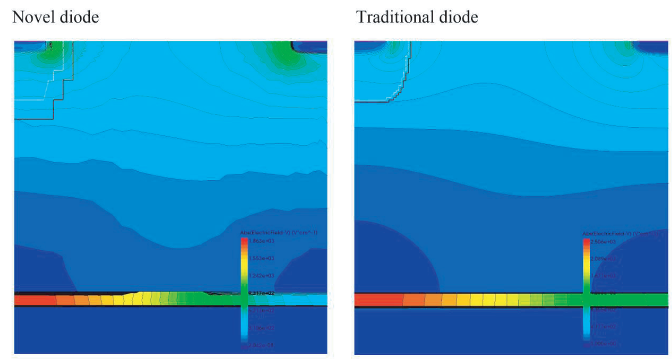

FIGURE 6. Electric field distributions of both the novel SPIN diode and the traditional device.

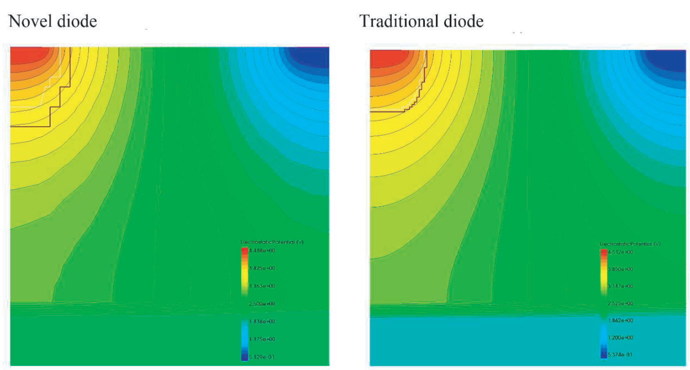

FIGURE 7. Electric potential distributions of both the novel SPIN diode and the traditional device.

$1 \times 10^{18}\ \mathrm{cm}^{-3}$, significantly compromising the microwave performance of the device. In contrast, the novel SPIN diode incorporating a SiGe compensation region demonstrates a concentration difference rate of only 50% at $y = 10\ \mu\mathrm{m}$, thereby greatly improving the uniformity of the solid-state plasma distribution. A comparative analysis of the solid-state plasma concentration curves at $x = 40\ \mu\mathrm{m}$ is presented in Fig. 4, revealing a declining trend of plasma concentration with increasing depth. The internal solid-state plasma concentration in the new device is approximately 1.5 times that of the traditional device, thereby validating the effectiveness of the proposed device design.

To visually illustrate the distribution of solid-state plasma within the device, this study simulated the two-dimensional plasma distributions of both the novel SPIN diode and the traditional device under a bias voltage of 2 V, as shown in Fig. 5. The figure reveals that the compensation SiGe region located at the center of the intrinsic region effectively enhances the concentration of solid-state plasma in the central area of the device. Consequently, the concentration of solid-state plasma within the intrinsic region exceeds $1 \times 10^{18}\,\mathrm{cm}^{-3}$, leading to a significant reduction in carrier recombination and attenuation within the intrinsic region. Conversely, for the traditional device, a noticeable concentration gradient of solid-state plasma is observed, with lower concentrations closer to the center of the intrinsic region. Additionally, the average concentration of solid-state plasma within the intrinsic region of the traditional device remains below $1 \times 10^{18}\,\mathrm{cm}^{-3}$. Fig. 6 and Fig. 7 present a comparison of the electric field and electric potential distributions in the steady state between the devices.

4. CONCLUSION

This study presents a significant advancement in the field of silicon-based plasma devices, addressing the limitations associated with traditional designs. The introduction of a novel heterogeneous SPIN diode with multi-region compensation effects presents a promising solution for improving the concentration and distribution uniformity of solid-state plasma. By incorporating SiGe regions within the device, we successfully enhance the concentration and distribution uniformity of solid-state plasma, thereby improving the microwave characteristics and overall performance of antenna systems. These findings contribute to the development of reconfigurable antenna technologies and hold promise for future applications in wireless communication systems.

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