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Investigation of Surface PiN Diodes for a Novel Reconfigurable Antenna

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Abstract—Solid state plasma antenna based on surface PiN diodes is characterized by its wide radiation range, good stealth characteristics, compatibility with traditional microelectronic technology, and dynamic reconfiguration, which has very broad application prospects in the fields of wireless communication, radar, and remote sensing. To improve carrier concentration and uniformity within theintrinsic region, a novel SPiN diode with a double-layer structure is described in this paper. This structure can compensate the concentration attenuation at the midpoint of the 'i' region, which makes carriers have a more uniform distribution with high concentration, and carrier concentration within the 'i' region twice of the traditional SPiN diode. A Si/Ge/Si heterojunction diode is also researched in this paper. These results indicate that a fully reconfigurable semiconductor plasma antenna based on this novel surface PiN diode is achieved to meet the currently-growing communication requirements.

1. INTRODUCTION

Nowadays, solid state plasma reconfigurable antennas based on surface PiN (SPiN) diodes have been developed in the last several years to meet the currently-growing communication requirements. SPiN diodes are the basic elements in which the concentration of carrier should achieve a relatively high level. The investigated SPiN diodes in other papers have a single-layer structure to act as radiation elements. In this case, the distribution of carrier concentration within the intrinsic region is low and uneven, which greatly influences the performance of the plasma antenna [1, 2]. Thus, a SPiN diode with a novel structure should be developed to solve this problem. Silicon-based solid state plasma reconfigurable antenna based on surface PiN diodes is characterized by its wide radiation range, good stealth characteristics, compatibility with traditional microelectronic technology, and dynamic reconfiguration.

Since SPiN diodes are not used as classical switches, their structure is significantly different from the traditional diodes. The conventional PiN diode is a vertical device, where the central intrinsic region is stacked between heavily doped P+ and N+ regions. The intrinsic region dimensions are selected based on the off-state isolation, reverse breakdown voltage, and switching speed goals. A surface PiN diode with a single-layer structure has also been presented in other papers. In this structure, the carrier concentration within the 'i' region is low and uneven due to the carrier's diffusion and recombination. The closer the position is to the midpoint and bottom of the 'i' region, the lower the carrier concentration is [3, 4]. To design a high integration silicon-based reconfigurable antenna, carrier concentration and uniformity should be further improved. In this paper, a novel SPiN diode with a double-layer structure is presented. This structure can compensate the concentration attenuation at the midpoint of the 'i' region, which makes carriers have a more uniform distribution with high concentration. The high

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conductivity of silicon is dependent on the number of carriers present, and at sufficiently high carrier concentration it can appear metallic to realize the radiation characteristics of the solid state plasma reconfigurable antenna.

2. STRUCTURE MODEL

The conventional SPiN diode (single-layer structure) reported in other papers is shown in Fig. 1. This diode is a very simple semiconductor device. Similar to the bulk PIN diode, it requires only two regions: N+ and P+ embedded in a highly resistive substrate with metal contacts [5].

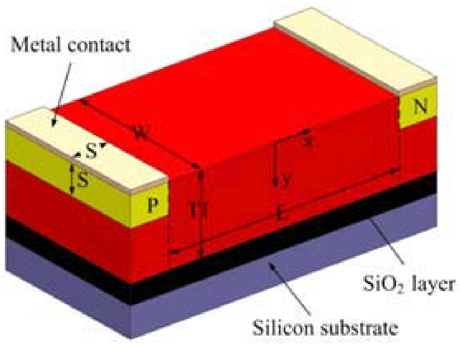

Figure 1. Structure of the previous SPiN diode length of the 'i' region $= L = 100\,\mu\mathrm{m}$, $T1 = W = 80\,\mu\mathrm{m}$, $S = 5\,\mu\mathrm{m}$.

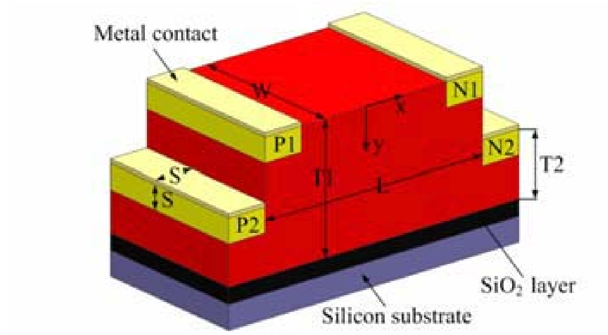

Figure 2. Structure of the novel SPiN diodelength of the 'i' region $L = 100\,\mu\mathrm{m}$, $T1 = W = 80\,\mu\mathrm{m}$, $T2 = 40\,\mu\mathrm{m}$, $S = 5\,\mu\mathrm{m}$.

Compared with the conventional diode, a novel SPiN diode (double-layer structure) with uniformly heavily doped ($10^{19}\,\mathrm{cm}^{-3}$) P (P1 and P2) and N (N1 and N2) regions is shown in Fig. 2. High resistivity n-type silicon ($n_i = 10^{14}\,\mathrm{cm}^{-3}$) is specified for the top device layer and bottom substrate. P and N type doping give rise to identical static carrier profiles, except at junction regions because of the different diffusion rates of carriers in all directions. In this device, the carriers are confined to the top silicon layer by Silicon-on-Insulator (SOI) technology.

The resistivity of the intrinsic region is very high when the SPiN diode is not biased (in the OFF state). Thus, the intrinsic region shows open circuit and like a dielectric. Contrarily, in the ON state, i.e., biased in a forward bias, the PiN diode is characterized by a low resistance of the plasma region. In this case, the plasma region is conductive enough (a quasi-metallic layer) to couple with the external electromagnetic wave to realize the microwave characteristics of the SPiN diode. Essentially, the thickness of the plasma region should be within 2–3 skin depths to provide an effective short circuit at RF field. In addition, all fabrication steps of this diode are compatible with a standard silicon line [6].

3. SPIN DIODE DEVELOPMENT

The diode with a double-layer structure has a high carrier concentration within the 'i' region because the P and N regions at the bottom can compensate the concentration attenuation at the midpoint of the 'i' region. The Sentaurus TCAD software used for the 2D device simulations allows determination of carrier concentration and I-V characteristics for specified device dimensions. All simulations are performed at room temperature, $T = 300\,\mathrm{K}$. The SPiN diode works at high-level injection condition, and quasi-neutral condition is valid in this paper.

Figure 3 shows the carrier density profiles biased at 2 V, from which we can see that carrier concentration at the bottom of the 'i' region has been almost doubled compared with the single-layer SPiN diode. A large difference between these two types of diodes starts to appear at $y = 40\,\mu\mathrm{m}$, and a larger difference is obtained when the depth is increased. This difference can be more clearly revealed in Fig. 4. The carrier density profiles are quite similar in all parts. These results demonstrate the usefulness of the double-layer structure.

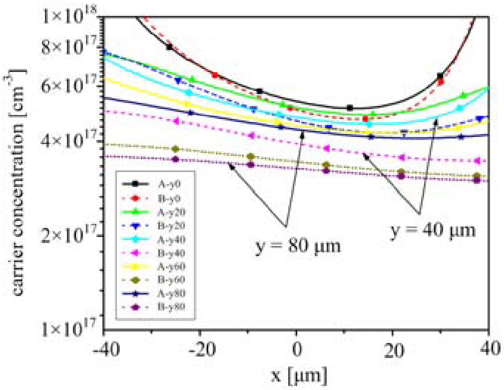

Figure 3. Carrier density profiles of the novel diode (A) and single-layer diode (B).

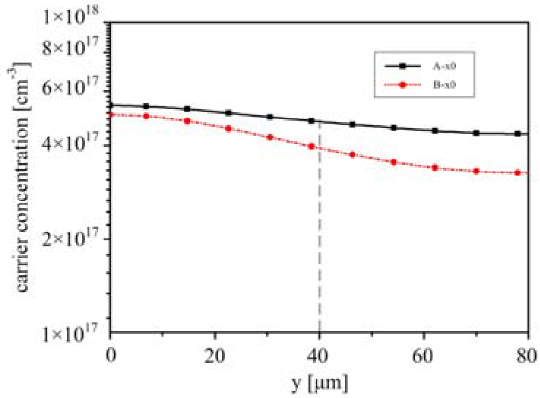

Figure 4. Comparison of carrier density profiles of the novel diode (A) and single-layer diode (B).

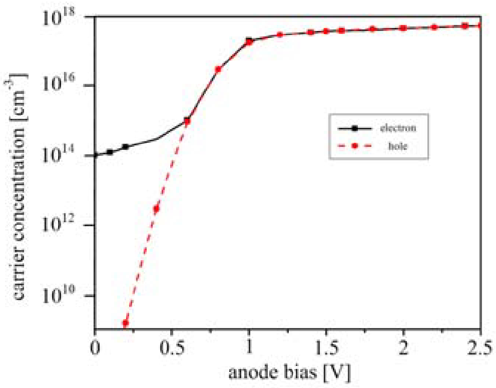

Figure 5. Carrier density profiles ($x = 0\,\mu\text{m}$, $y = 5\,\mu\text{m}$).

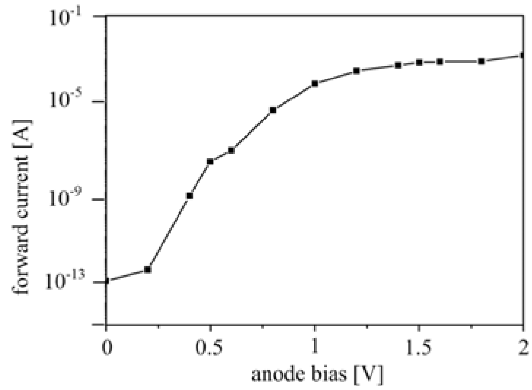

Figure 6. I-V characteristic for the novel diode.

Figure 5 shows the relationship between the carriers (electron and hole) concentration ($x = 0\,\mu\text{m}$, $y = 5\,\mu\text{m}$) and forward bias in the double-layer structure diode. At a given point, the carrier density is increased with forward bias, and the forward turn on voltage is approximately 0.7 V. Fig. 6 shows I-V characteristic for the diode with double-layer structure. From which it can be seen that the forward current increases with increasing bias, and this diode shows a saturation state when the supplied voltage reaches 1 V.

The potential distribution and doping parameters of this diode are shown in Fig. 7. In this diode, there is a uniform potential difference within the top silicon layer, and the voltage drop distributes evenly on this diode. These results prove the feasibility and correctness of this design. The distribution of the carriers within the novel SPiN diode bias at 2 V is also presented in Fig. 8. The double-layer structure compensates the concentration attenuation at the midpoint of the intrinsic region, carrier concentration exceeding $10^{18}\,\text{cm}^{-3}$ when this diode is biased at 2 V, and there are high concentration solid state plasma within the whole region.

4. COMPARISON OF THE SI/SI/SI AND SI/GE/SI DIODES

The Si/Si/Si homojunction diode with a double-layer structure is already studied in the previous section, in which high resistivity n-type silicon ($n_i = 10^{14}\,\text{cm}^{-3}$) was specified for the diode layer and carrier wafer. Considering the demand of high carrier concentration, a Si/Ge/Si heterojunction diode is studied in this section, where germanium is specified for the 'i' region. This diode will further improve the

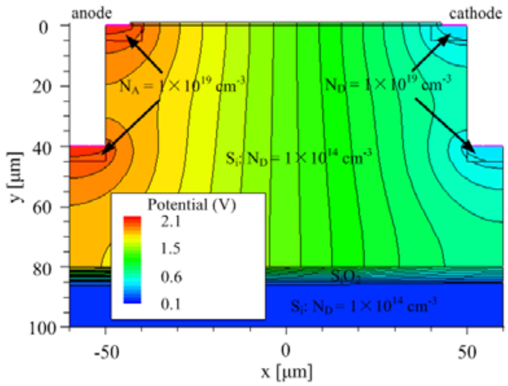

Figure 7. Potential distribution of the novel diode.

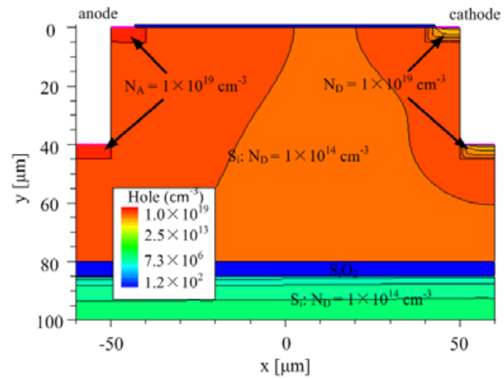

Figure 8. Distribution of the concentration of the novel diode.

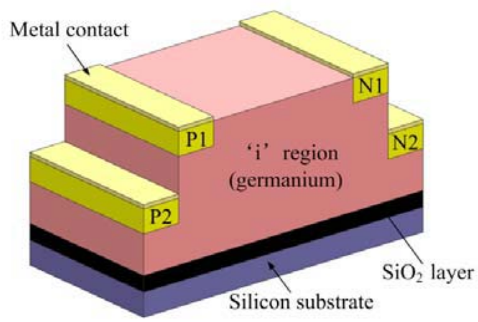

Figure 9. Structure of the heterojunction diode.

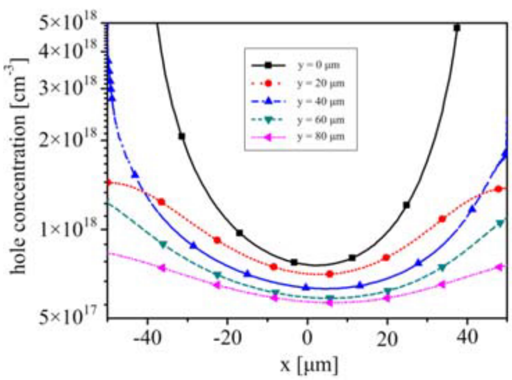

Figure 10. Carrier density profiles of the heterojunction diode.

injection ratio and carrier concentration. Other parameters of the heterojunction diode are the same as the previous homojunction diode. The diagram of this diode is shown in Fig. 9.

Figure 10 shows the carrier density profiles of the heterojunction diode biased at 2 V, and carrier concentration within the 'i' region is increased approximately three times. These results suggeste that a Si/Ge/Si heterojunction diode with a double-layer structure can further improve carrier concentration within the 'i' region effectively, and heterojunction structure is considered superior.

5. CONCLUSION

Based on the previous results, the double-layer structure improves carrier concentration effectively compared with the traditional single-layer diode. To further improve the level of carrier injection ratio, the Si/Ge/Si heterojunction diode is also discussed in this paper, which further increases carrier concentration within the 'i' region. These results indicate that a fully reconfigurable semiconductor plasma antenna based on this novel surface PiN diode with high carrier concentration has been achieved to meet the currently-growing communication requirements. It can also be used in high power electronic devices and other semiconductor fields. Theoretical analysis of this diode should be investigated in future work.

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