Simulation of InGaAs-Based Planar Nanodevices As Terahertz Rectifiers

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Abstract. A planar nanodevice, known as the self-switching diode (SSD), has a non-linear current-voltage characteristic that resembles a typical diode behaviour. Unlike other conventional diodes that depending on barrier junction or gate, SSD utilized its L-shaped trenches to exhibit non-linear I-V behaviour, which can be exploited for high-frequency operations. This paper presents technology computer-aided design (TCAD) rectification studies of two InGaAs-based SSDs connected in parallel with similar/different length operating at sub-terahertz frequencies and at zero bias. As expected, the combination of SSDs with the shortest length possess the highest cut-off frequency, and in this case, at approximately 0.35 THz. This is comparable with the recent proposed hybrid structure of SSD and planar barrier diode (SSD/PBD). In fact, it has lower leakage current than SSD/PBD which can reflect to a better rectification performance. (Keywords: Rectifier, Self-switching diode, Terahertz frequency).

1. Introduction
The increasing usage of the devices in the microwave and terahertz region has triggered the electronic industries to produce a rectifier that can cope with high frequency [1]. However, the conventional device such as PN-diode and plate diode are unable to operate in the high-frequency region due to RC time constant limitation and slow carrier movement inside the devices resulting in phase lag [2]. Besides, a majority carrier device operating in high-frequency regions such as back diodes and tunnel diode also face some issues such as circuit complexity, challenging fabrication process, and simply effect by RF burnout [3]. Furthermore, the fabrication of small devices required more lithography process, resulting in increased production cost. The fabrication of smaller devices causes a short channel effect limiting the device’s operation in high frequency [4]. In 2003, Song et al. proposed a planar rectifying nano-diode which offers a simpler, cheaper and faster fabrication process when compared to other diode-based rectifiers [5]. The device's planar structure allows it to operate at high speed in the high-frequency region due to a very low parasitic capacitance [6]. The device is realized by tailoring an isolating two L-trenches (Figure 1. (a)) between two electrodes (anode and cathode). The device's working principles illustrating a 2D field-effect transistor with gate to drain act as a short circuit and the L-trenches acting as double lateral gates. Furthermore, the induced electric field effect from surface charge along the lateral channel enables electronic transport to move in one direction [7].
The working operation of SSD is shown in Figures 1 (a) – 1 (e). As shown, a nonlinear current-voltage (I-V) characteristic can be generated due to changes in the depletion region thickness inside the device channel depending on the biasing voltage applied to the device [6]. From previous research, this diode has shown promising capability operating in millimeter wave and up to the terahertz frequencies [8]. SSDs has been simulated and fabricated in various materials including InGaAs [9,10], silicon [6], InAs/AlSb [11], and novel green material like graphene [12]. Recent research state that SSD coupled with PBD shown quite good performance with a peak rectification coefficient and zero bias rectification at ~19 V-1 and ~6 V-1, respectively [10]. Moreover, the estimated cut-off frequency of the device is ~360 GHz (0.36 THz). However, the fabrication of PBD might be challenging due to its nano-scale dimension with parameters that sensitive to the rectifying performance [10]. A combination of SSDs with different dimensions can be an alternative since SSDs are easily fabricated and less complex than PBDs.

Figure 1. (a) Atomic-force microscope image of SSD. (b) Depletion region induced at the interface between insulator (black colour) and semiconductor (white colour) at zero bias. (c) At V > 0, channel is opened due to smaller depletion region inside the device channel. Hence, current can flow across the device. (d) At V < 0, channel is closed due to thicker depletion region and subsequently block current from flowing across the device. (e) I-V behaviour of SSD [6].

As such, this paper presents the simulation work on two In$_{0.7}$Ga$_{0.3}$As-based SSDs, connected in parallel using a technology computer-aided design (TCAD) simulator. In the section of Simulation of Two Parallel InGaAs Self-Switching Diode, the material used, parameters (trenches width and length, channel width), and the electrical properties will be presented. Next, the section Characterization of Self-Switching Diode will discuss the input voltage and the cut-off frequency formulae. After that, the I-V characteristic, AC transient analysis and Cut-off frequency of each device are presented in Results and Discussion. Finally, the summary of this paper will be presented in the Conclusion.

2. Simulation of Two Parallel InGaAs Self-Switching Diode

Previously, an optimized structure of SSD has been characterized by NF Zakaria [13]. This optimized SSD structure is used in this work which has channel width, W of 70 nm and trench width, $W_t$ of 50 nm. The channel length, $L$ of two SSDs connected in parallel is manipulated in which their lengths are varied with $L = 0.4 \ \mu m$ and $L = 1.0 \ \mu m$. The electrical properties used for the simulated devices are as follows; uniform n-type In$_{0.7}$Ga$_{0.3}$As with a doping concentration of $1 \times 10^{17} \ \text{cm}^{-3}$, interface charge density, $\sigma = -3.75 \times 10^{11} \ \text{cm}^{-2}$, electron mobility without scattering, $\mu = 12,000 \ \text{cm}^2 \text{V}^{-1} \text{s}^{-1}$, contact resistivity of $1 \times 10^{8} \ \Omega \ \text{cm}^2$ which commonly used for THz devices, and temperature of 300 K for energy balanced model.
As shown in Figure 2, the background blue region is the In\textsubscript{0.7}Ga\textsubscript{0.3}As substrate; meanwhile, the purple region forming the L-shape is the insulator i.e., air. The two parallel L-shape of the SSD situated between two dark regions, which represent electrodes (anode and cathode).

![Figure 2](image-url)

**Figure 2.** The top view of two InGaAs SSDs, connected in parallel simulated in TCAD simulator.

### 3. Characterization of Self-Switching Diode

The voltage ranging from -1 V to 1 V is applied across the SSDs to analyse the device's I-V behaviour. After that, to mimic and analyse the output current characteristic in the high-frequency signal, AC transient analysis with 0.5 V sinusoidal input is executed without any external bias. The mean output current is extracted by applying the following formulae on Ac transient analysis,

\[ I_{\text{mean}} = \frac{1}{(t_1-t_i)} \int_{t_i}^{t_1} f(t_1) \, dt - \frac{1}{(t_2-t_i)} \int_{t_1}^{t_2} f(t_2) \, dt \quad (1) \]

in which

\[ t_2 = t_1 - T \quad (2) \]

where \( t_i \) is the initial time, \( t_1 \) is the transition time between positive to negative cycle, T is the period which is \( 1/f \) and \( dt \) is the discrete transient time of the simulation. The cut-off frequency of SSD is determined when the output waveform of the positive side is equal to negative side (positive – negative = 0) resulting in zero \( I_{\text{mean}} \) which results in zero rectifying properties. \( I_{\text{mean}} \) versus frequency graph is plotted to has a better insight of the cut-off frequency. To support the result, the obtained cut-off frequency is compared with cut-off frequency calculated by using formulae

\[ f_c = \frac{1}{2\pi R_s C} \]

where \( R_s \) is the resistance and \( C \) is the capacitance of the SSD. More details on \( R_s \) and \( C \) can be referred in [14] and [15] respectively.

### 4. Results and Discussion

Figure 3 shows the I-V characteristic of two InGaAs-based SSDs connected in parallel with the following combination of the device channel length; \( L = 0.4/0.4 \, \mu m, 1.0/1.0 \, \mu m \) and \( 1.0/0.4 \, \mu m \). As
can be observed, at V = 1 V SSDs with L = 0.4/0.4 µm has the highest forward current which is 14 µA. This is expected since a shorter channel length will provide shorter transmission channel for the carrier to transmit across the device. The other parallel SSDs have almost the same forward current, 12 µA, since the carriers follow the highest channel length, which is 1 µm. On the other hand, at V = -1 V the highest leakage current is -3 µA with L = 0.4/0.4 µm. This results from the short-channel effect as the channel's ratio to width (L/W) of the device has decreased. In such a case, under reverse bias, the lateral regions' potential may not be able to delete the device's channel, so that the barrier preventing the current flow disappears and hence, an inverse leakage current flows across the device. However, the leakage current reduced for SSD with L = 1.0/0.4 µm and 1.0/1.0 µm.

Figure 3. The I-V Characteristic of two parallel SSDs for L = 0.4/0.4 µm, 1.0/0.4 µm and 1.0/1.0 µm.

The input voltage has a sinusoidal waveform with an amplitude of 0.5 V at difference frequencies (0.1 GHz, 10 GHz, and 50 GHz). As shown in Figure 4 (a), at 0.1 GHz, the rectification is good since the output current is following the input voltage. It is worth to note that, the sinusoidal input voltage is applied to the SSD without any biasing. Hence, as expected, from the I-V behaviour, SSD with L = 0.4/0.4 µm exhibits the highest output current since its turn-on voltage is the closest to 0 V. As the applied signal frequency increase as shown in Figure 4 (b) and Figure 4 (c) (10 GHz and 50 GHz, respectively), the output current starts to dephasing from the input voltage. However, it still shows a positive average value, also known as the mean current.

Figure 4. AC transient analysis of SSD with 0.5 V sinusoidal input voltage at frequency = (a) 1 GHz, (b) 10 GHz, and (c) 50 GHz.

The mean current is calculated using equation (1) and plotted in the graph against the input voltage frequency, as shown in Figure 5. The device's highest cut-off frequency is ~350 GHz for SSD L =
0.4/0.4 µm, and the lowest cut-off frequency of the device is ~185 GHz for SSD with L = 1.0/1.0 µm. Meanwhile, the cut-off frequency of SSD with L = 1.0/0.4 µm is ~220 GHz. We can conclude that the shortest channel length exhibits a higher cut-off frequency. Using equation (3), the calculated cut-off frequency and the estimated cut-off frequency obtained from the graph are tabulated in Table 1.

![Graph of mean current against frequency of the input voltage.](image)

**Figure 5.** Graph of mean current against frequency of the input voltage.

| Parallel SSD length, L, | Cut-off frequency gain | Theoretical cut-off frequency | Percentage difference | Leakage Current (µA) at V = -0.5 V |
|-------------------------|------------------------|-------------------------------|-----------------------|-----------------------------------|
| 0.4/0.4 µm              | ~350 GHz               | 366 GHz                       | 4.37 %                | 1.28                              |
| 1.0/1.0 µm              | ~185 GHz               | 209 GHz                       | 11.48 %               | 0.00                              |
| 1.0/0.4 µm              | ~220 GHz               | 251 GHz                       | 12.35 %               | 0.46                              |
| SSD/PBD [10]            | ~360 GHz               | -                             | -                     | 2.00                              |

As shown in Table 1, the theoretical cut-off frequency is higher than the cut-off frequency estimated from the simulation. This is expected since the fringe capacitance of the parallel SSD is excluded in the theoretical calculation. The SSD/PBD still has slightly higher cut-off frequency compared to the two parallel SSD. However, SSD/PBD exhibits a high leakage current (~2 µA at 0.5 V), affecting the rectification performance [10]. Therefore, a combination of SSDs with similar/different dimensions can be an alternative to SSD/PBD in order to produce devices with good rectification performances and high cut-off frequencies.

### 5. Conclusion

A combination of two parallel SSDs with rectification in the sub-THz region is proposed and simulated. The I-V characteristic of two parallel SSDs with length 1.0/0.4 µm is lower in terms of leakage current compared to two parallel SSD with length 0.4/0.4 µm. On the other hand, the cut-off frequency of two parallel SSDs with length 1.0/0.4 µm has the highest cut-off frequency compared to two parallel SSDs with L = 1.0/1.0 µm and L = 1.0/0.4 µm. The conclusion that can be made from the results is by combining two different lengths of SSDs, connected in parallel, the rectification...
performances in terms of nonlinear properties and cut-off frequencies of the devices can be optimized, and are comparable with the rectification performance of the SSD/PBD combination.

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