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Effect of channel length to the frequency response of Si-based Self-Switching Diodes using two-dimensional simulation

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Abstract. A planar nanodevice, known as the self-switching diode (SSD) which can be exploited as a high-speed rectifier in a wide range of applications. The non-linearity in the *I-V* characteristic of the SSD structure has been aimed for rectification application at GHz frequencies is reported. In this work simulation has been conducted on Si-based SSD structure with 230 nm L-shaped channels using ATLAS device simulator under the channel length range of 0.5 μm to 1.3 μm. Furthermore, the validity of the cut-off frequency has also been described using a theoretical value of f_t at zero bias. The results showed that the optimization in the channel length of the SSD can assist the high cut-off frequency of SSD rectifying behavior to efficiently operate as microwave rectifier.

Introduction

The SSD was introduced by [1] with a simple planar device architecture that requires just one step of lithography process and without any doping junction, as depicted in Figure 1 (a). The L-shape of the device channel produces a nonlinear characteristic of device operation, which is the potential barrier inside the device channel is significantly important as shown in Figure 1 (b). An asymmetrical potential barrier prevents reverse carriers on one side from passing to the other side. In SSD, asymmetrical potential barrier can be achieved by etching two insulating trenches (L-shaped) to produce non-linear *I-V* characteristic [2]. The non-linearity in the *I-V* characteristic of the Si-based SSD structure allows for the rectification performance, which can be exploited in various high frequency applications including healthcare, telecommunication, security and energy harvesting.

The basic principle was explained in [1], where the geometry of the SSD devices can affect the *I-V* characteristic. In literatures, longer channel will increase the interaction between the channel and the flanges (L-shaped), and results in better field effect control [3]. Moreover, the channel length can be used to determine their current oscillation amplitudes, where frequency is inversely proportional to channel length [2, 4].

As such, this is the main study of this work which can designing the optimum channel length of SSD rectifiers.

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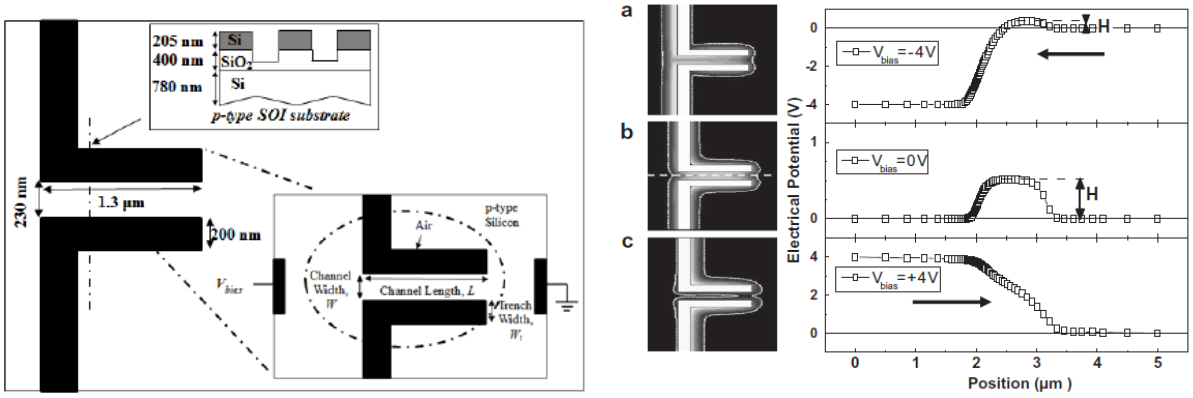

(a) (b)

Figure 1: (a) A typical topview image of a single SSD. Lower inset shows the large-scale view including contacts, ground and biasing electrode. Upper inset shows the cross-section of SSD perpendicular to the channel [5]. (b) Potential energy profile along the SSD channel at with different bias voltage [5].

Methodology

Prior to this work, a p-type Si-based SSD structure was analyzed using ATLAS device simulator. The different simulator software (Medici) whereby an experimental data [5] on Si-based SSD were used to validate the model and parameter settings of the ATLAS device simulator. Our simulation has successfully been validated with [5] and reported in [6]. The validated model is then used for another SSD design, based on alteration of device geometry.

The SSD was introduced by [1] with a simple planar device architecture that requires just one step of lithography process and without any doping junction, as depicted in Figure 2. These devices are made with silicon-on-insulator (SOI) technology and operated at room temperature. The two trenches of the L-shape with channel width *(W)* of 230 nm, channel length *(L)* of 1.3 μm and trenches width (W_t) of 10 nm with air as the insulating trenches as the conduction channel. The geometrical parameter is a key that affect the electrical model in SSD. The Si mobility and temperature room carrier density are 2.45×1016 cm^{-3} and 400 cm^2/Vs respectively. The left electrode in the model was set to be an applied voltage, V_{bias} and the other one was grounded. The frequency dependence of an SSD is found by altering the length of the trenches.

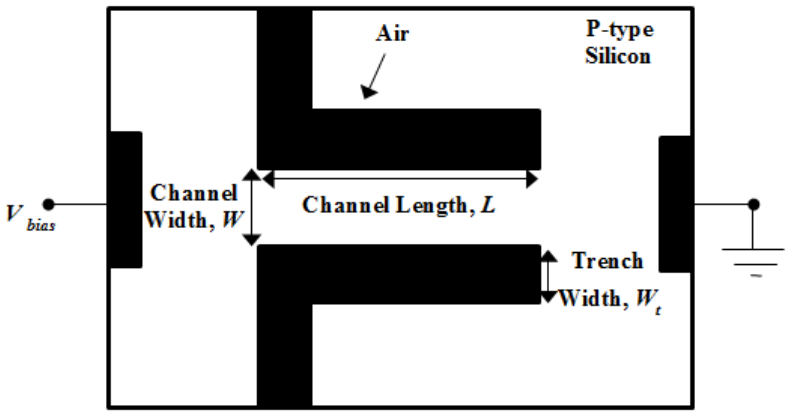

Figure 2: Top view of a SSD structure which has two terminals with L-shape p-type Si-based. The black areas are etched and act as an insulating layer. In our simulation, W = 230 nm, L = 0.5 μm to 1.3 μm and W_t = 10 nm.

Result and Discussion

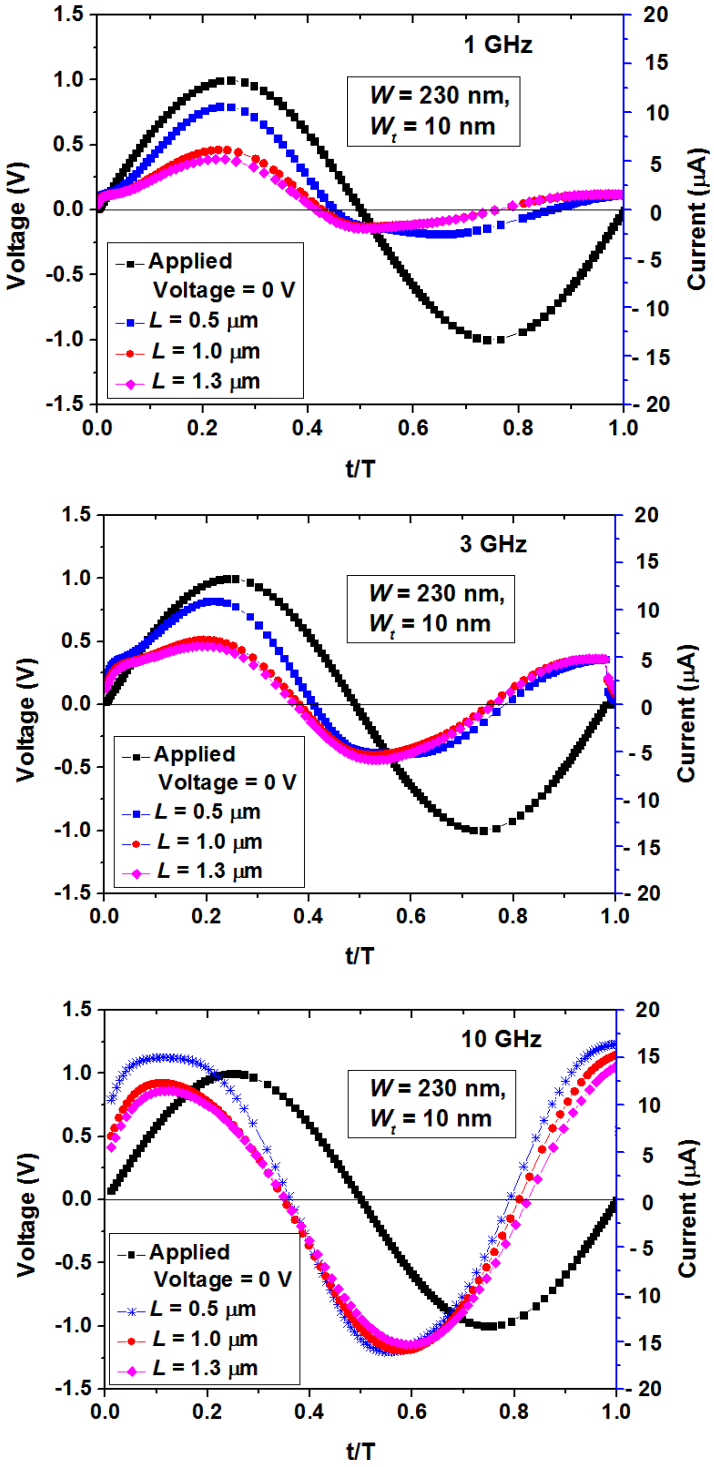

Figure 3: Current response and input voltage signals at frequencies 1 GHz, 3 GHz and 10 GHz with amplitude of 1.0 V. *W* = 230 nm, *Wt*= 10 nm and *L* from 0.5 μm to 1.3 μm. Note that T is the period corresponded to the frequencies of the input voltage signals.

Figure 3 shows the sinusoidal input voltage signals, which is the current response of the SSD with the amplitude of 1.0 V and the frequencies of 1 GHz, 3 GHz and 10 GHz at room temperature. As can be seen, for 1 GHz, the rectification is fairly good, where a shorter length of SSD is expected to have higher average current as shown by the *I-V* graph. At higher frequency (3 and 10 GHz), the output current signal starts to dephase with respect to the input signal. Nevertheless, each of the output current is still a positive average value.

The average current value for the p-type Si-based SSD as a function of *f* being swept from the ranges of 1 – 20 GHz is shown in Figure 4. The intrinsic cut-off frequency, f_t obtained for the p-type Si-based SSD is approximately between 12–20 GHz. This is a typical order of f_t value for electronics devices that used Si as a substrate [7,8]. As expected, high cut-off frequency of SSD rectifying behavior depends on the channel length, where f_t will be higher for a shorter channel length device.

Alternatively, in order to investigate the validity of the cut-off frequency of the Si-based SSD device obtained in the simulation, a theoritical value of f_t at zero bias has been estimated. which has considered the resistance and parallel capacitance of the SSD device. The f_t of an SSD can be represented as [7]

$$f_t = \frac{1}{2\pi R_S \left(C_{jo} + C_p\right)} \tag{1}$$

where R_s is the series resistance of the SSD, C_{jo} and C_p are the junction capacitance at zero bias and parasitic capacitance respectively. In order to calculate the series resistance, we consider an ideal diode current of the SSD device as a function of bias voltage, which can be extracted from logarithmically linear part of *I-V* curve [9].

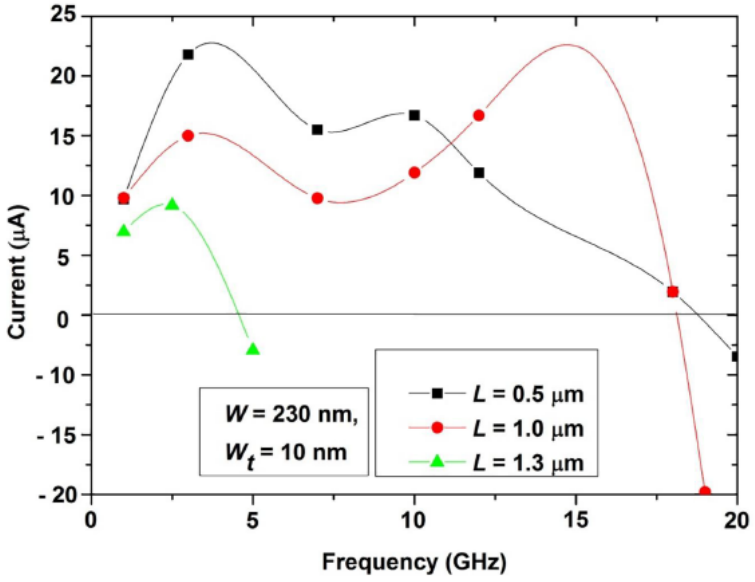

Figure 4: Mean output of the SSD current with respect to the frequency of periodic input voltage with amplitude of 1.0 V, applied to the SSDs with *W* = 230 nm, *Wt*= 10 nm and *L* from 0.5 μm to 1.3 μm.The intrinsic cut-off frequency of the p-type Si-based SSD was ~19 GHz.

The total parallel capacitance was calculated as (Aberg & Saijets, 2005)

$$C_{jo} + C_p = \varepsilon_0 W_\upsilon \left(2\frac{L+D}{t_{etch}} \right) \quad (2)$$

where ε_0 is the permittivity of free space, W_v is the SOI thickness and other geometry parameters are defined in Figure 5. Table 1 compares the f_t for simulated and calculated result with the varied L values. Based on this comparison, it was found that the results of simulation and calculation are in slightly different but still in the range of GHz frequencies and linearly increased with increasing L.

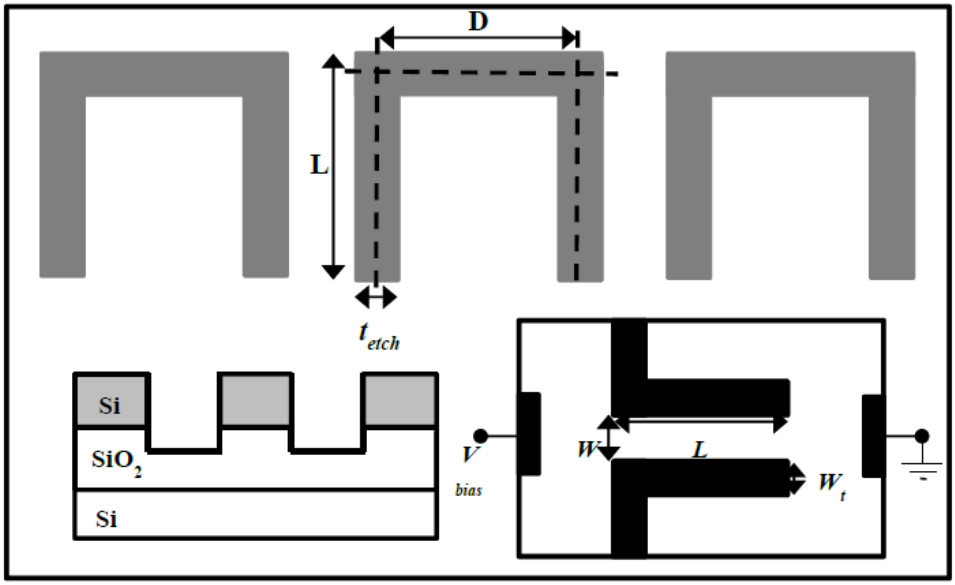

Figure 5: A top view image of SSDs connected in parallel with L = 0.5 μm to 1.3 μm, D = 0.55 μm and t_{etch} = 10 nm. Below right inset shows the top view image of a single SSD including biasing electrode and ground. Below left inset shows the cross-section of SSD perpendicular to the channel with vertical width, *Wv* of the device ~ 1 μm.

Table 1: Comparison between simulation and theoretical for cut-off frequency of the p-type Si-based SSD.

Channel Length, L (μ m)	**SOI thickness, W_v (μ m)**	**Simulation f_t (GHz)**	**Calculated f_t (GHz)**
0.5	1.0	~ 19	31
1.0	1.0	~ 18	25
1.3	1.0	~4	19

Conclusion

Using 2D ATLAS device simulator, we reported that the Si-based SSDs with different channel length in order to achive high rectification performance. In this work, the highest intrinsic cut-off frequency approximately 19 GHz was obtained with a channel length of 0.5 μm for p-type Si-based SSD. This result is a typical order of cut-off frequency value of Si material in electronic devices. GaAs and InGaAS are the high-mobility semiconductor materials and can also be utilized in SSD rectifiers to improve the cut-off frequency.

Acknowledgments

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