Frequency Response Modeling and Saturation Power Improvement of Lateral-PIN Germanium Photodetectors

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Abstract: A frequency response model is developed for Germanium photodetector under large input optical powers. The model agrees well with the measurement results. Furthermore, a simple approach using parallel photodetection is demonstrated with ≥3-dBm saturation power.

1. Introduction

Over the past decade, germanium photodetectors integrated on silicon chip have been well developed and much improvement has been achieved in their fabrication process, responsivity, bandwidth, and reliability [1, 2]. Nowadays, commercial germanium photodetectors integrated on silicon photonic chips have been shipped in large volume worldwide for high-speed optical interconnects. However, high-speed photodetectors with high saturation power are necessary in many real-world applications. For example, the maximum input optical power could be as large as 4 dBm for 400GBASE (4 × 100Gbps) transceiver [3]. Under such a large input power, high-speed germanium photodetectors become saturated and exhibits severe degradation in their frequency response. Hence, improving the saturation power and the dynamic range of germanium receivers remains a critical issue for silicon photonics industry.

Among various types of germanium photodetectors, vertical-PIN (VPIN) [4] and lateral-PIN (LPIN) [5] are two most commonly used structures. VPIN has a narrower junction width and higher electrical filed under a given bias, which helps to reduce the impact of large input optical power on its frequency response. However, its bandwidth is limited by the RC (resistor-capacitor) time constant while its responsivity is reduced by absorption of metal electrodes on the top. On the other hand, LPIN has much smaller junction capacitance, so it can reach almost 100% quantum efficiency with an adequate absorption length. At the same time, its smaller capacitance also alleviates the RC time constant limit. Therefore, LPIN has the potential to reach higher bandwidth for applications beyond 100G. However, LPIN has intrinsically a weaker electrical field in its junction area, and compared to VPIN, it is more vulnerable to frequency response degradation under large input optical powers. Hence, a better understanding of the frequency response LPIN with large optical inputs could give us insights on how to improve its saturation power.

In this paper, we developed a model for the frequency response of germanium photodetector, taking into full consideration of the device doping profile, space charge field distribution and the transit time of photo-generated carriers. With such a model, the bandwidth performance of LPIN under input optical powers from -10dBm to 3dBm is well predicted and in good agreement with experimental measurement. In addition, a simple approach using parallel photodetection are proposed to improve the frequency response of LPIN under large optical inputs. An LPIN with parallel photodetection exhibits a significant improvement in its saturation power and no obvious degradation in its bandwidth with an input optical power as high as 3dBm, meeting the requirements of 400GBase applications.

2. LPIN structure and its frequency response modeling

2.1. *Germanium LPIN*

Fig. 1(a) shows the cross-section of the germanium photodetector (Ge PD) with a LPIN junction. The germanium absorption region is partially embedded in silicon ridge. The external bias voltage is applied through p-type and n-type doped silicon on two sides. With incoming light propagating through the germanium material, optical absorption generates electrical carriers in the intrinsic region, which are then separated by electrical field (shown in Fig. 1(b)), resulting in photocurrent at the electrodes. The frequency response of germanium photodetectors is mostly determined by two factors, the RC time constant and the transit time of photogenerated carriers. The former is limited by the junction capacitance of LPIN, its series resistance and other parasitics. The later depends on the velocity of the carrier drift and the length of the LPIN depletion region. Fig. 1(c) shows the equivalent frequency response model of a photodetector. For an LPIN germanium photodetector, its junction capacitance remains very small (usually <5 fF) due to a large separation between P and N implant regions. In this case, the simulation results show that the bandwidth of an LPIN is mostly decided by the carrier transit time as shown in Fig. 1(d).

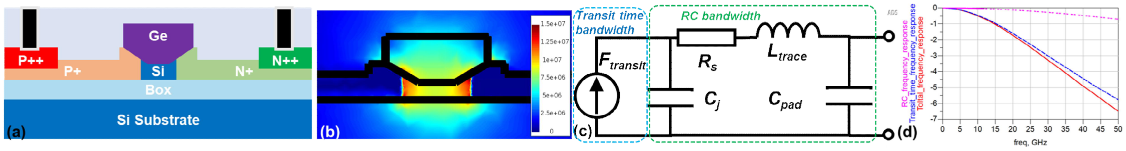

Fig. 1 (a) Cross section of LPIN Ge PD. (b) Electrical field distribution in LPIN Ge PD. (c) Equivalent frequency response model. (d) The total frequency response (red line), transit-time response (blue dash) and RC response (pink dot) of LPIN Ge PD.

2.2. *Transit-time response model*

Fig. 2 shows the transit-time model and its numerical simulation approach. A finite element method (FEM) based numerical solver is established to calculate the electrical field distribution and the drift of electrons and holes in LPIN Ge-Si structure, taking consideration of the doping profile and space-charge field due to the photogenerated carriers. In addition, other effects such as trap-assisted recombination and the impact ionization generation in Si and Ge are also included in the model. In order to calculate the transit-time response, a pulsed light is launched into the model and the time-varying photocurrent represents the impulse OE (optical-electrical) response of the LPIN. Finally, the Fourier transform of the impulse response of the photocurrent leads to the frequency response. For simplification and expediting simulations, an equivalent 1D PIN can be used to model the full LPIN structure by drift length equivalence.

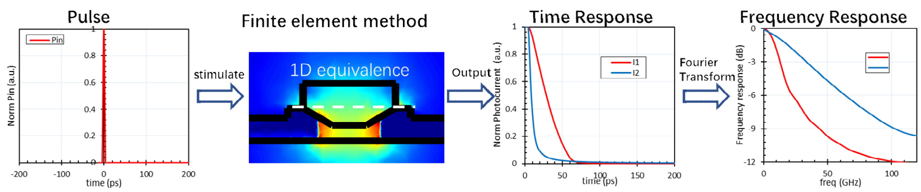

Fig. 2 Transit-time response model

The transit-time response of LPIN is simulated in following steps. First, based on the doping profile, the electrical field distribution and carrier drift velocity in LPIN is calculated without incident light, and this serves as the initial condition of the LPIN. Next, a CW incident light is injected into the LPIN and the photogenerated carrier is calculated based on the first step. As show in Fig. 3(a), the electrical field in germanium decreases as the light power increases. This is due to the screen effect of the space charge (i.e., the photogenerated carriers) in the junction. At the same time, the increase in photocurrent also leads to the larger voltage drop on doped silicon, which also reduces the voltage applied on Ge region. Based on the steady-state solutions in step 2, a pulsed light (t = 4ps) is incident into the junction to calculated the time response of the photocurrent. Fig. 3(b) and (c) shows the distribution of the photogenerated carriers and electrical field at different time when light pulsed with 0-dBm power is launched into the junction. From the results, we can see that the OE response (i.e., the photocurrent) is dispersive in time with a tail as long as 180 ps. It takes ~60 ps for electrical field to recover after the light is off.

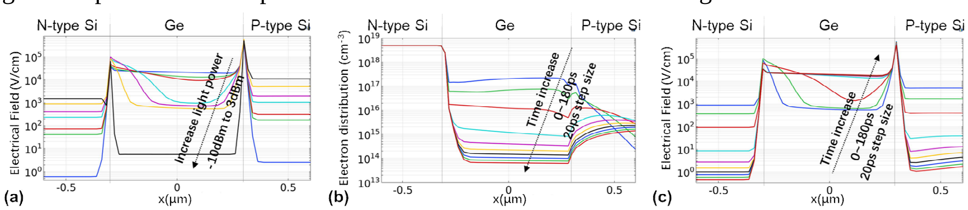

Fig. 3 (a) Steady-state electrical field distributions under different input optical power (-10~3dBm); (b) Distribution of photogenerated electrons at different time (0~180ps); (c) Electrical field distribution at different time (0~180ps).

2.3. *Results*

To verify our transit-time response model, LPIN Ge PDs are designed and fabricated with 130nm silicon photonics process. The bandwidth of LPIN Ge PD is limited by a long transit time in the relatively thick germanium. The widths of germanium are chosen as 0.5, 0.6 and 0.7μm. The length of germanium is 20μm for efficient absorption. The measured responsivity is >0.9 A/W for each design. Fig. 4 shows the measured frequency response of LPIN Ge PDs and our simulations agree well with the measurement results. With different incident optical power under -3 dBm, one sees that there is little change in the frequency response, as shown in Fig. 4(a). However, the frequency response degrades rapidly when power is increased over 0 dBm, which is well predicted by the model. When the input optical power is increased to 3 dBm, the LPIN Ge PD shows severe degradation in its frequency response. Fig.

4(b) shows the frequency response of LPIN with 0 dBm input optical power and under different bias voltage from -1 to -3 V. As the bias voltage decreases, the electrical field in germanium decreases. As a result, the transit time of carriers becomes longer and the bandwidth decreases. Fig. 4(c) shows the dependence of the frequency responses on germanium widths (V_{bias} = -3V, P_{in} = 0dBm). It is obvious that the electrical field decreases with increasing width, which results in a decrease in bandwidth.

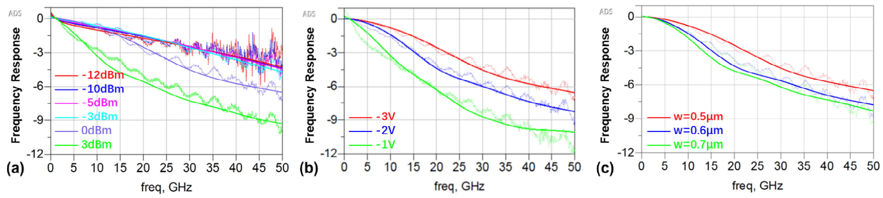

Fig. 4 (a) Frequency response of a LPIN Ge PD with 0.5μm width (V_{bias} = -3V) with different input optical powers. (b) Frequency response of a LPIN Ge PD with 0.5μm width (P_{in} = 0dBm) with different bias voltages. (c) Frequency response of LPIN Ge PDs with different germanium widths (V_{bias} = -3V, P_{in} = 0dBm).

Since large input power and high bandwidth is both necessary in many applications, there are several methods to optimize the frequency response under large input. One approach is to increase the electrical field with large bias voltages or smaller germanium widths. However, the germanium width is limited by the germanium epitaxy process of the foundry and increasing the operation voltage has a negative effect on the device reliability and reduces the lifetime of the Ge PDs.

Another method is to reduce carrier concentration in germanium by structure designs [6]. In our case, we distributed the incident optical power and use 2 and 4 parallel photodetection. The light splits one or two times by 1×2 MMIs before going into each photodetector as shown in Fig. 5 (a). In this case, the incident optical power to each Ge PD can be reduced by 3dB and 6dB, respectively. The cathodes and anodes of parallel photodetectors are connected to merge the photocurrent. Since the junction capacitance of single LPIN is <5fF, the capacitance of 4 parallel photodetector is <20fF, which is still small enough to ignore the RC circuits bandwidth (> 100GHz as shown in Fig. 5 (b)). Fig. 5 (c) and (d) show the measured frequency response of LPIN Ge PD with 2 and 4 parallel photodetection. Comparing to a lumped LPIN in Fig. 4(a), 3dB and 6dB improvement in the optical saturation power with the same bandwidth performance. 9dB improvement can be achieved with 8 parallel design, for which the RC bandwidth is still > 70GHz.

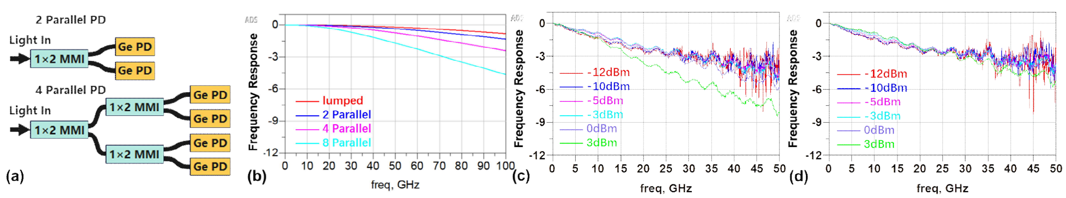

Fig. 5 (a) Schematic of 2 and 4 parallel PDs. (b). RC frequency response of single and 2/4/8 parallel PDs. Frequency responses of 2(c) and 4(d) parallel LPINs (w = 0.5μm, V_{bias} = -3V) with different input optical powers.

3. Conclusions

LPIN germanium photodetector has a large responsivity and ultra-low capacitance with a great potential to reach high bandwidth. However, its frequency response degrades under lager input optical power (⩾0dBm), because of the weak electric field in its depletion region. We developed a model to predict germanium photodetector bandwidth under large optical inputs, taking into account of the doping profile and the space charge field of the photogenerated carriers. The simulations match well with the measurement results for input optical power varying from -12dBm to 3dBm. Parallel photodetection is demonstrated to alleviate the impact of large optical inputs. A 3~6 dBm improvement in saturation optical power can be achieved for our designs with 2 and 4 parallel photodetection.

4. References

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