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# New Ge-gate IR Phototransistor based on Doping Engineering Aspect: Photodetection Properties and Circuit Level Investigation

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***Abstract*— In this paper, a novel Infrared phototransistor (IR PT) design based on Ge-gate with doping engineering aspect (DE) is proposed. Comprehensive investigation based on accurate numerical modeling of the device photodetection properties is carried out. The impact of gate doping engineering on the Ge-gate IR PT FoM metrics is performed and thoroughly discussed. It is revealed that the proposed PT structure can provide enhanced photoresponse with low dark noise effects. Moreover, a systematic circuit level investigation of an optical logic switch based on the proposed Ge-gate IR PT with GE aspect is performed. The obtained results emphasize the ability of the proposed PT structure for promoting enhanced optical gain with superior switching capabilities. Promoting enhanced photoresponse, low noise and improved switching capabilities, this innovative strategy of GE can be used for the design of efficient CMOS-compatible optical communication systems.**

***Keywords*— Ge; doping engineering, Responsivity, Infrared, Communication, CMOS**

## I. Introduction

Silicon (Si) photonics constitute a promising technology for achieving better integration capabilities, which is highly suitable for the emerging chip-level optical communication systems [1-4]. As an important building block of the latter systems, photorecievers should satisfy various performance requirements to take chip-level optical communication systems based on Si photonics platform beyond the proof of the concept [5]. This outlook necessitates the development of Si-based photodetectors (PDs) capable for promoting a good photoresponse at common Infrared (IR) communication window. In this regard, Si-based photodetectors encounter several challenges mainly related to its intrinsic optical limitation, where their low cutoff wavelength of 1.1 µm, high recombination losses and low absorption capabilities prevents their deployment for optical interconnection systems [5-8]. Alternatively, the successful growth of less-defects Germanium (Ge) on silicon platform has opened doors for continuous development of IR chip-level optical communication systems [9]. This is owing to the potential of Ge-based devices for extending the optical photoresponse capabilities of PDs beyond 1.1 µm. Following this perspective, much research focus is devoted to the development of high-performance Ge PDs offering monolithic integration on Si platform [9]. In this context, several Ge-based IR sensors were investigated, showing a great promise for promoting enhanced photodetection properties [10-13]. Despite this benefit, the developed devices face various limitations such as high dark current, low sensitivity and high power consumption still persist. The latter challenges should be addressed for further boosting Ge-based PDs.

Ge-gate phototransistors have drawn tremendous attention due to their potential to replace conventional PDs and photodiodes by offering an internal optical gain and Complementary Metal-Oxide-Semiconductor (CMOS) processing compatibility [14-16]. The cornerstone of this device resides on introducing a Ge sensitive-gate, which can modulate the channel conductivity behavior under IR light-irradiation. This innovative Metal Oxide Semiconductor Field Effect Transistor (MOSFET)-based device has demonstrated the ability for achieving high responsivity values at 1.55 µm communication window. However, the device still exhibits a high dark current, causing extensive noise effects. Besides, the switching capabilities of the device require further improvements in order to enhance the performance and to reduce the overall power consumption of the emerging optical communication systems. Therefore, new design strategies are of urgent need to boost the performance of Ge-gate phototransistors.

Doping engineering (DE) strategy has been emerged as an effective approach for improving several devices such as nanoscale transistors and photodetectors [17-19]. This strategy has enabled achieving better device performances. Intuitively, DE aspect can potentially enhance the performance of Ge-gate phototransistors (PTs). In this regard, the main aim of this work is to investigate the role of introducing Ge-gate with doping engineering aspect in enhancing the phototransistor photodetection capabilities and optical switching characteristics. The Ge-gate is considered with two dissimilar regions with different doping levels. The influence of doping concentration of the Ge gate region near the drain side on the photoresponse characteristics of the investigated device is carried out. The phototransistor optical switching properties are analyzed by implementing the proposed device with DE aspect in an inverter gate circuit. It is revealed that the proposed device based on Ge-gate with DE paradigm shows enhanced IR photoresponse, low dark-noise effects, and high switching capabilities, making it highly appropriate for the emerging optical communication systems.

## II. DESIGN AND MODELING FRAMEWORKS

The main idea behind the proposed PT structure resides on suggesting two Ge-gate regions with dissimilar doping concentrations $N_1$ and $N_2$. The latter parameters present the doping levels near the source and drain sides, respectively. In this framework, Fig.1 illustrates a descriptive scheme of the proposed Ge-gate PT structure with DE strategy. This figure shows the device structure, consisting of MOSFET tree-terminal device platform with $SiO_2$ gate oxide, where $d_{SiO2}$ denotes its thickness, $L=L_1+L_2$ represents the channel length, with $L_1$ and $L_2$ are respectively the first and the second regions lengths. The working principle of the investigated device is based on the well known photogating effect. The latter can be modulated by introducing dual doping regions in the Ge-gate. This can promote effective IR-light absorption capabilities, while maintaining a good control of the channel conductive behavior.

To examine the photodetection characteristics of the proposed Ge-gate PT device, accurate numerical models based on SILVACO Technology Computer Aided Design (TCAD) commercial software are developed [20]. In this context, ATLAS module is exploited for the modeling of carrier transport mechanism in MOSFET platform. To this extent, drift-diffusion model is used for the device transport mechanism. Furthermore, FLDMOB model is used to consider the impact of the high field velocity saturation on the Ge-gate electrical behavior. Moreover, the band-gap narrowing (BGN) model is introduced to take into account consider the effect of the heavily doped Ge-gate on the material electronic properties. On the other hand, finite element numerical technique is exploited to self-consistently solve the continuity equations and the Poisson equation given as follows

$$div(\varepsilon \nabla \psi) = -\rho \qquad (1)$$

with $\rho = q(p - n + N_a)$

$$\frac{1}{q} div(\vec{j_n}) - R_n + G_n = 0 \qquad (2)$$

$$-\frac{1}{q} div(\vec{j_p}) - R_p + G_p = 0 \qquad (3)$$

where ε is the absolute permittivity, $\psi$ represents the electrostatic potential, q denotes the electron charge, ρ refers to the net charge density, which is related to the P-type Si channel doping concentration ($N_a$) and free electron and hole carrier densities (n, p). Besides, $J_n$ and $J_p$ are the current densities of electrons and holes, respectively, $G_n$ and $G_p$ denote the generation rates of electrons and holes, while $R_n$ and $R_p$ represent the associated recombination rates. The later are calculated by including Shockley-Read-Hall (SRH) recombination model [20]. The excess carrier in the Ge-gate based on DE aspect under 1.55 µm monochromatic light illumination is calculated using FDTD method using Luminous module, where the Ge material refractive index and extinction coefficient are taken from [21]. The excess carrier will produce an optical voltage, which modulates the channel conductivity behavior. The device design

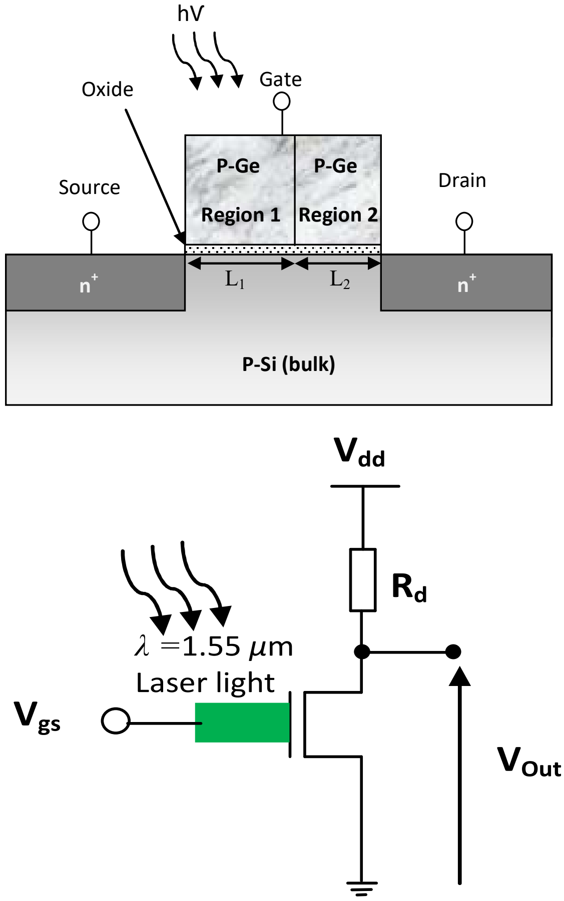


Fig.1. (a) Cross-sectional view of the proposed Ge-gate phototransistor based on DE aradigm. (b) Investigated optical inverter circuit based on the proposed Ge-gate PT device with DE aspect on MOSFET platform

parameters used for our numerical modeling are summarized in Table.1.

It is important to note that the material physical parameters are taken from Sopra database.

Finally, mixed mode module available in SILVACO software is used to implement the proposed IR ge-gate phototransistor design based on DE aspect in an inverter gate circuit using a specific load resistance of 20 kΩ as it is shown in Fig.1 (b). this TCAD modeling feature uses advanced numerical algorithms, which are regarded efficient and reliable for analyzing different properties involving small signal AC, DC and transient modes.

TABLE I. DEVICE DESIGN PARAMETERS USED IN OUR NUMERICAL INVESTIGATION

| Parameters | Optimal values |
|---|---|
| Channel doping | $2\times10^{17}$ $cm^{-3}$ (P-type) |
| Source/Drain doping | $10^{20}$ $cm^{-3}$ ($N^+$-type) |
| Silicon thickness ($t_{si}$) | 0.20 µm |
| Channel length (L) | 180 nm |
| Gate oxide thickness ($d_{SiO2}$) | 5 nm |
| Ge-gate thickness ($d_{Ge}$) | 200 nm |
| Length of the first Ge-gate region ($L_1$) | 90 nm |
| Length of the second Ge-gate region ($L_2$) | 90 nm |

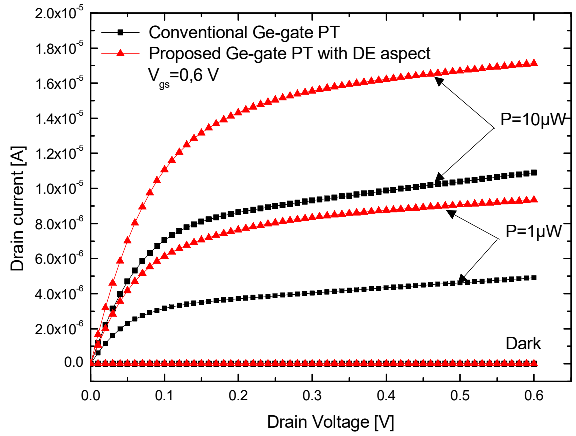


Fig. 2. $I_{ds}$ versus $V_{ds}$ of the proposed Ge-gate PT with DE aspect at dark and illuminated by 1.55 µm light and power 1µW to 10 µW compared with that of the conventional phototransistor with applied $V_{gs}$ = 0.6, $N_1$=5.10$^{16}$ cm$^{-3}$, $N_2$=5.10$^{18}$ cm$^{-3}$.

## III. Results and Discussions

To assess photoresponse properties of the proposed Ge-gate PT based on DE aspect, its transfer characteristics under dark and IR illumination conditions are extracted and compared to that of the conventional counterpart as it is described in Fig.2. It is important to note that the obtained I-V characteristics associated with the conventional device shows a good agreement with that provided in the previous work [14]. Clearly, the proposed Ge-gate PT device with DE strategy exhibits superior IR photosensing as compared to the conventional design, showing higher photocurrent densities at dissimilar optical powers. This outstanding improvement is attributed to the effect of introducing DE aspect, promoting enhanced absorbance capabilities and allowing better control of the channel conductivity. In other words, the use of dual gate regions with dissimilar doping levels leads to induce significant changes on the channel surface potential, thereby giving rise to enhanced derived

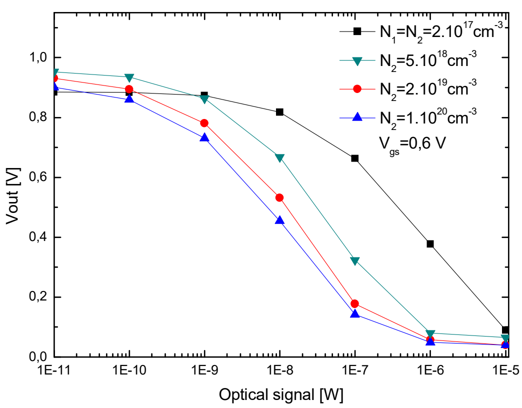


Fig. 3. Vout against input optical power of the investigated device for different $N_2$ levels compared with conventional inverter with Ge-gate PT, with $N_1$=2×10$^{17}$ cm$^{-3}$ , $N_{ch}$=2 × 10$^{17}$cm$^{-3}$, $V_{gs}$ = 0.6 V .

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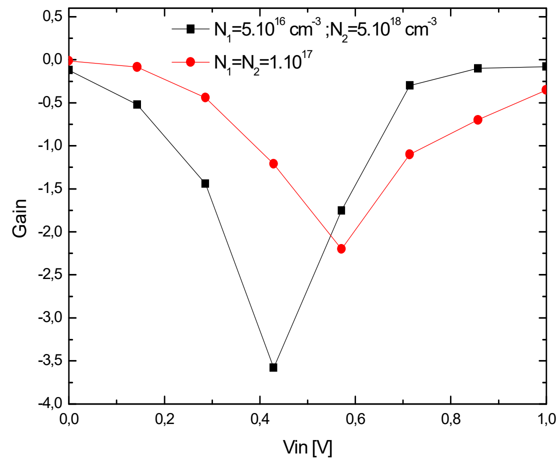
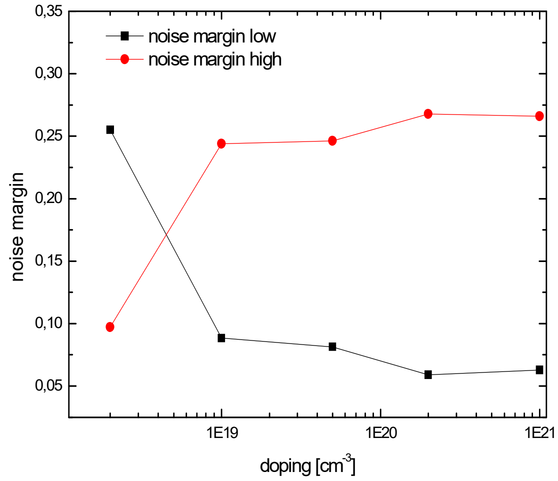



(a)




(b)

Fig. 4. Variation of the optical gain associated with the proposed Ge-gate PT design with DE approach. (b) Noise margin low and high against the Ge-gate doping level ($N_2$) near the drain side.

current capabilities. These encouraging results inspire implementing the proposed device in an optical inverted circuit and investigating the effect of DE on the device switching properties as it is shown in Fig.1 (b). Accordingly, Fig.4 (b) compares the output voltage versus the optical power for both optical inverter circuits based on the investigated Ge-gate PTs with and without doping engineering using various doping level values near the drain side. A load resistance of 20 kΩ, a gate voltage of 0.6 V and an operating voltage of 1 V are used for optical inverter circuit simulations. It can be observed from this figure that the proposed device with DE aspect shows high switching capabilities as compared to the conventional structure, promoting enhanced optical gain values. This is mainly due to the use of DE strategy allowing better optical swing characteristics. In addition, the use of an optimized Ge-gate DE can allow achieving near 1 V at off-state conditions. Interestingly, the proposed Ge-gate PT offers better switching performances at lower optical power densities in comparison with the conventional counterpart, indicating its capability for giving an appropriate photoresponse using ultralow power consumption from the emitter stage.

To further investigate the device performance, the optical gain as a function of the input voltage is extracted for both analyzed Ge-gate PTs with and without DE aspect and then depicted in Fig.4 (a). The proposed device with DE paradigm offers superior optical gain values over a large input voltage window. This improvement is mainly due to the enhanced photosensing characteristics of the device when DE strategy is included. In addition, the proposed PT structure with optimized DE configuration allows reaching an enhanced optical gain at lower operating voltages, thus emphasizing its ability for offering low-power consumption optical communication systems. Fig.4 (b) shows noise margin parameters as a function of the Ge-gate doping level in the second region near the drain side. This figure demonstrates the ability of the proposed Ge-gate structure for offering low noise effects at high and low states of the inverter. This is attributed to lower dark noise effects associated with the proposed device, which leads to enhance the device dynamic range.

Finally, to show the strength of the proposed device, Table.1 illustrates an overall performance comparison concerning the device FoM metrics between the proposed PT structure and the conventional one without DE aspect. It can be concluded from this table that the use of Ge-gate with engineered doping profile opens up new pathways for enhancing the device photodetection and switching capabilities, where a high optical gain of 3.58, current ratio of 69.6 dB and a low swing factor of 86 mV/dec are achieved. Therefore, by combining MOSFET platform and Ge-gate with DE strategy, we were able to design high-performance and low noise PT offering enhanced optical commutation properties.

TABLE II. COMPARISON BETWEEN THE INVESTIGATED GE-GATE PT STRUCTURES WITH AND WITHOUT OPTIMIZED DE ASPECT

| **Parameters** | **Ge-gate with Uniform doping $N=2.10^{17}$ cm$^{-3}$** | **Ge-gate with DE ($N_1=5.10^{16}$ cm$^{-3}$, $N_2=5.10^{18}$ cm$^{-3}$)** |
|---|---|---|
| $I_{ON}/I_{OFF}$ ratio [dB] | 63.2 | 69.6 |
| Subthreshold Swing [mV/dec] | 101.10 | 86.61 |
| Threshold voltage [V] | 0.7 | 0.65 |
| Optical Gain | 2.52 | 3.58 |

## IV. CONCLUSION

In this work, a new Ge-gate PT design based on DE strategy is proposed and numerically investigated. Accurate numerical models of the proposed device are carried out. The obtained results show the ability of the proposed device with DE aspect for offering enhnaced photoresponse characteristics, where a high photocurrent even at low optical powers is reached by introducing engineered doping profile in the Ge-gate. Moreover, a circuit level investigation of the proposed device is performed by implimenting it in an optical inverter circuit. It is demonstrated that the proposed device with DE approach can enhance the optical inverter switching capabilities, showing an improved optical gain of 3.58. In addition, the investigated IR PT based on DE allows reducing noise and power consumption, where a high $I_{ON}/I_{OFF}$ ratio of 69.6 dB is achieved, which is much higher than that of conventional device. This makes the proposed PT device potential alternative photoreciever to design high performance logic optical switch circuits, which are highly suitable for the emerging optical communication systems on silicon photonics technology.

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