Numerical Investigation of a New GeSn MIR Phototransistor based on IGZO TFT Platform

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Abstract— In this paper, a new Mid-Infrared phototransistor (MIR PT) design based on InGaZnO (IGZO) thin-film (TF) and GeSn sensitive layer is proposed. Exhaustive study of the device photosensing properties is carried out using accurate numerical models based on FDTD technique. It is revealed that the proposed PT structure can provide enhanced responsivity with reduced dark current. Importantly, the influence of the Sn mole fraction on the device MIR spectral photoresponse and switching characteristics is investigated. It is found that the use of 15% of Sn containing can allow achieving the highest responsivity at 2 µm optical window, while maintaining a low dark noise effects. The optimized device is the implemented in an optical inverter gate in order to study the device switching characteristics. The obtained results demonstrate the capability of the proposed PT structure for promoting enhanced optical gain with high switching capabilities. Therefore, these findings open the perspective for the design of alternative MIR sensors, offering improved photoresponse and low noise, which are highly suitable for newly emerging CMOS-compatible optical communication and optoelectronic applications.

Keywords— GeSn; Mole fraction, Responsivity, Mid-IR, Communication, IGZO

I. INTRODUCTION

During the last few years, silicon photonics has gained a substantial research attention, opening new pathways for achieving better integration capabilities [1-4]. This technology consists of various building blocks including emitters, waveguides and photorecievers [5]. The latter building block should fulfill several criteria such as high responsivity within the adopted communication window, low dark noise effects and reduced power consumption [6]. Unfortunately, Silicon Photodetectors (Si-PDs) cannot satisfy these requirements because of the intrinsic limitation of Silicon material, exhibiting a low cutoff wavelength of 1.1 µm, high recombination losses and low absorption capabilities [7-10]. The successful grown of Germanium (Ge) on Silicon-On-Insulator (SOI) platform with reduced defects has opened doors for the design and elaboration of new generation of Infrared (IR) photosensors that can operate in optical windows beyond 1.3 µm [11]. In this perspective, various photoreciever structures based on Ge and Silicon-Germanium (SiGe) alloy were developed, showing the ability for offering an acceptable photoresponse at 1.55 µm communication wavelength [12-17]. Although this benefit, the indirect nature of the band gap associated with these materials limits the device responsivity. Besides, Ge and SiGe based photosensors have reached their limits regarding the device performance and cutoff wavelength. This makes theme unable to follow the actual stage of maturity concerning optical communication systems based on Si photonics platform. The latter technology requires photorecievers that can perfectly operate at 2 μm wavelength. The latter spectral window is highly desirable because of its safety, enhanced capacity limit of optical fiber and low solar noise effects [18]. Great efforts in establishing the platform of this path have been devoted to exploring alternative sensitive materials that can cover a wide Mid-Infrared (MIR) spectral window beyond 1.55 µm [19-23]. In this context, Germanium-Tin (GeSn) compound is particularly attractive for reaching this objective, offering fascinating properties such as narrow tunable direct band gap, high carrier mobility, compatibility with Metal-Oxide-Semiconductor Complementary (CMOS) processing and high absorption coefficient over the MIR spectral band [24-26]. So far, much research focus is devoted to the realization of GeSn MIR photosensors that can operate in the emerging 2 µm optical window. Accordingly, various monolithically integrated on Si optoelectronic photorecievers were proposed, demonstrating a great promise for promoting enhanced MIR photoresponse [25-27]. However, several challenges still persist and should to develop highly-efficient be addressed optical interconnects. For instance, high Sn containing GeSn films promote extended cutoff wavelength, however, this leads to induce severe degradation-related to lattice mismatching effects. In addition, Sn rich GeSn films show a very low resistivity, which can in turn increase the dark current. This effect can severely raise the device noise effects and power dissipation. Thus, new design methodologies are necessary to surmount these concerns.

Recently, Indium Gallium Zinc Oxide (IGZO) thin-filmtransistors (TFT) platform has been widely exploited for the development of highly-responsive low noise UV and Visible light phototransistors by staking matched sensitive films [28-29]. Intuitively, this strategy can be used for the design of GeSn phototransistor based on IGZO TFT platform. To do so, the aim of this work is to numerically analyze the performance of a new Phototransistor (PT) structure based on combined IGZO TFT platform and GeSn sensitive layer. The effect of the Sn mole fraction on the device performance is also investigated. The device optical switching properties are analyzed by implementing the proposed PT in an inverter gate circuit. It is revealed that the proposed device based on combining IGZO TFT platform and GeSn sensitive layer shows enhanced, broaden IR photoresponse, low dark-noise effects, and high switching capabilities, making it highly appropriate for the emerging optical communication systems.

II. DEVICE STRUCTURE AND MODELING

METHODOLOGIES

Fig.1 illustrates a descriptive scheme of the proposed PT structure with GeSn MIR sensitive layer on IGZO TFT platform. This figure shows the device structure, consisting of IGZO tree-terminal device with SiO₂ gate oxide, where d_{SiO2} denotes its thickness, L represent the channel length, d_{IGZO} and d_{GeSn} are respectively the channel and GeSn capping layer thicknesses. The drain and source extremities are separated from the introduced GeSn film by considering voided regions to prevent current flow over GeSn film. The idea behind this structure is to achieve high photoresponse with reduced dark noise effects. In fact, in darkness, the generated current will be very low due to the use of IGZO TFT, while under MIR light illumination, the photogenerated carriers will be transferred to the back channel of IGZO TFT creating a current path. This will give rise to an important drain current [3].

To examine the optoelectronic performances of the device, accurate numerical models based on SILVACO Technology Computer Aided Design (TCAD) commercial software are developed [30-32]. Accordingly, ATLAS module is used to model the transport mechanism of IGZO TFT platform. In this context, drift-diffusion model is incorporated and finite element method is utilized to self-consistently solve the continuity equations and the Poisson equation given as follows

$$div(\varepsilon \nabla \psi) = -\rho$$
(1)
with $\rho = q(p - n + n_t - p_t - p_d + N_d)$
$$\frac{1}{q} div(\vec{j}_n) - R_n + G_n = 0$$
(2)

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

where ε is the absolute permittivity, ψ represents the electrostatic potential, q denotes the electron charge, p refers to the net charge density, which is related to the n-type IGZO channel doping level (N_d), free electron and hole carrier densities (n, p), and the shallow donor-like densities (p_d). The net charge density depends also on the charged states of conduction and valence band tail (n_t, p_t) . In this context, exponentially decayed band tail states and Gaussian distributions of mid-gap states are introduced by taking into consideration density of states (DOS) model, which can incorporate acceptor-like VBT, donor-like CBT and shallow donor-like deep level band using a Gaussian profile. These parameters are taken from recently published work in order to be very close the device realistic behavior [33]. This can be efficient for achieving a good agreement with the experimental results. Besides, Jn and Jp 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



Fig.1. Cross sectional view of the proposed GeSn/IGZO MIR TF PT.

and R_p represent the associated recombination rates. The later are calculated by including Shockley-Read-Hall (SRH) recombination model. The excess carrier in the GeSn film under 2 µm light irradiation is estimated using FDTD method using Luminous module, where the GeSn material refractive index and extinction coefficient at dissimilar Sn mole fractions are taken from [34].

The absorbance at 1.55 μ m wavelength of the inserted GeSn sensitive layer is calculated using the following formula

$$A(\lambda) = \frac{\int_{V} \frac{1}{2} \left| \vec{E}_{y}(\vec{r}) \right|^{2} \omega \varepsilon_{0} \varepsilon_{i}^{"}(\lambda) dV}{\int_{S} \frac{1}{2} \operatorname{Re}\left\{ \vec{E}_{y}(\vec{r}) \times \vec{H}^{*}(\vec{r}) \right\} dS}$$
(4)

where λ denotes the wavelength, A is the absorbance, ε_0 and ε_i'' denote respectively, the permittivity of the vacuum and the complex dielectric constant extracted from the exploited refractive index of GeSn alloy using different Sn containing, S and V are respectively the film surface and volume. Besides, E_y denotes the electric field in the vertical direction, \vec{H}^* refers to the complex Magnetic field conjugate, w refers to the angular frequency.

Finally, mixed mode module available in SILVACO software is used to implement the proposed MIR phototransistor structure in an inverter gate circuit using a specific load resistance of 20 Ω .

III. RESULTS AND DISCUSSIONS

To assess the device photoresponse characteristics, Fig.2 shows I_{ds} - V_{gs} characteristics of the proposed PT devices with GeSn film and IGZO TFT platform under darkness and 2 μ m MIR light irradiation with V_{ds} =10 V, P_i=1 mW/cm², d_{IGZO} =20 nm and d_{GeSn} =150 nm and Sn containing of 10 % and 15%. Clearly, the proposed PT device with GeSn capping layer exhibits high MIR photodetection capabilities



Fig. 3. *I*_{ds}-*V*_{gs} characteristics of the investigated PT devices based on GeSn sensitive film and IGZO TFT platform with dissimilar Sn containing under under darkness and *MIR*-light irradiation conditions.

represented by the high photocurrent densities in a large operating voltage range. Moreover, the use of high Sn containing can allow achieving higher photocurrents. This is mainly due to the high absorption coefficient of Sn rich GeSn alloys. Basically, a high amount of photogenerated electron/hole pairs are transferred to the back IGZO channel by the action of the vertical electric field, enabling a high drain current under illumination conditions. On the other hand, it is obvious from this figure that the device based on high Sn mole fraction allows reducing the dark current density of the PT. This interesting property is ascribed to high work function of GeSn material with high Sn content, leading to modulate the channel conductivity thereby promoting reduced drain current in darkness conditions.

To further investigate the effect of Sn mole fraction on the device performances, Fig.3 shows the variation of both I_{ON}/I_{OFF} ratio and device responsivity associated with the proposed PT structure as a function of Sn containing in the introduced GeSn sensitive film. Obviously, this figure demonstrates the ability of the proposed structure for bridging the gap between high responsivity and low dark



Fig. 3. Variation of both device responsivity and ION/IOFF ratio as a function of the Sn mole fraction in the introduced GeSn photosensitive layer with $\lambda{=}1.55~\mu\text{m},~V_{ds}{=}10~V,~P_i{=}1~\text{mW/cm}^2,~d_{IGZO}{=}20~\text{nm}$ and $d_{GeSn}{=}150~\text{nm}.$

noise effects. It can be seen that the device FoM metrics increases with the Sn mole fraction increase until reaching the highest values at x=15 %. In this context, the proposed device reaches a superb responsivity of 525 A/W. after this specific value of Sn mole fraction, the device responsivity slightly decreases due to the effect of GeSn with high Sn level on the channel conductivity behavior. This infers the complex optoelectronic behavior of the investigated PT device based on GeSn capping layer on IGZO TFT platform.

Basically, phototransistors based on IGZO TFT platform are highly appropriate for the design of efficient optical communication systems due to its high capability of integration with silicon photonics platform. To further assess the performance of the proposed device based on GeSn active film and IGZO TFT platform, the device is implemented in an optical logic switch circuit as it is shown in Fig.4 (a). The latter figure depicts the investigated circuit, which is modeled using mixed mode module available in SIVACO package. A load resistance of 10 k Ω , a gate voltage of 0.5 V and an operating voltage of 1 V are used for optical inverter circuit simulations. To get a global regarding the device optical insight switching





Fig. 4. Investigated optical inverter circuit based on the proposed PT device with GeSn sensitive film and IGZO TFT platform. (b) output voltage as a function of the incident power for both proposed device and conventional one based on Ge-gate MOSFET structure.

characteristics, Fig.4 (b) compares the output voltage versus the optical power for both optical inverter circuits based on the proposed GeSn/IGZO TF PT and the conventional Gegate MOSFET-based phototransistor reported in our previous work [3]. It can be observed from this figure that the proposed device shows high switching capabilities as compared to the conventional structure, promoting enhanced optical gain. This is mainly due to the use of IGZO thin-film transistor technology allowing better swing properties. In addition, the use of this platform can allow achieving near 1 V at off-state conditions and enhanced noise margin parameters. This is attributed to lower dark noise effects associated with the proposed device, which leads to enhance the device dynamic range. More importantly, the proposed device begins to switch-on at very low optical power densities, indicating its capability for giving an appropriate photoresponse using ultralow power consumption from the emitter stage.

IV. CONCLUSION

In this work, a novel IR PT based on combined GeSn and IGZO TFT platform is proposed. Numerical models are developed to investigate the device photoresponse performances under IR light exposure. The effect of introducing GeSn on IGZO channel as well as Sn containing on the optoelectronic characteristics of the phototransistor are also analyzed. It is revealed that the insertion of GeSn film with optimized Sn mole fraction allows improving the device photodetection capabilities by promoting enhanced responsivity value of 525 A/W and a high Ion/IoFF ratio of 161 dB, which are much higher than that of Ge-based PT Afterwards, we performed a circuit level device. investigation by implimenting the optimized PT device in an optical inverter gate to assess the switching cappabilities of the device. It is found that the proposed PT based on GeSn sensitive film and IGZO TFT platform open up the route for achieving an enhanced optical gain with low noise effects. This makes it potential alternative PT for the emerging optical communication systems.

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