Proposal and demonstration of lock-in pixels for indirect time-of-flight measurements based on germanium-on-silicon technology

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Abstract: We propose the use of germanium-on-silicon technology for indirect time-of-flight depth sensing as well as three-dimensional imaging applications, and demonstrate a novel pixel featuring a high quantum efficiency and a large frequency bandwidth. Compared to conventional silicon pixels, our germanium-on-silicon pixels simultaneously maintain a high quantum efficiency and a high demodulation contrast deep into GHz frequency regime, which enable consistently superior depth accuracy in both indoor and outdoor scenarios. Device simulation, system performance comparison, and electrical/optical characterization of the fabricated pixels are presented. Our work paves a new path to high-performance time-of-flight sensors and imagers, as well as potential adoptions of eye-safe lasers (wavelengths > 1.4 μm) that fall outside of the operation window of conventional silicon pixels.

Index Terms: Indirect time-of-flight measurement, lock-in pixel, silicon photonics, germanium-silicon, photodetector.

1. Introduction

The construction of three-dimensional (3D) images is vital to a variety of applications such as hand tracking, facial recognition, 3D object scanning/printing, simultaneous localization and mapping (SLAM) for indoor/outdoor navigations, surveillance, and light detection and ranging (LiDAR) for autonomous vehicles, to name a few. There are a least four categories of techniques that are well studied in the literature, i.e., passive/active stereovision [1], structured light imaging [2], direct time-of-flight (TOF) sensing via single photon avalanche photodiode (SPAD) and time-to-digital converter (TDC) [3], and indirect TOF sensing via lock-in pixel [4]. In particular, the indirect TOF system has been a popular choice due to its direct acquisition of a depth information without additional computational algorithms, simple laser light projector without complex optical modules for spatial coded patterns, and low power consumption with respect to pixel number scaling. The principle of the indirect TOF system is essentially based on a homodyne detection operated at a radio frequency (RF) $f_m$, in which the roles of a local oscillator/mixer/detector are replaced by a single lock-in pixel, to demodulate the transmitted laser light that is initially modulated at $f_m$, then reflected from an 3D object, and finally received by the lock-in pixel. Consequently, the phase of the laser light can be extracted by detecting the low-frequency signal amplitudes, which indirectly maps the distance that the laser light traverses.

Various lock-in pixels have been analyzed and implemented using silicon (Si) technology, in which their demodulations are usually achieved through capacitive switching devices, such as a one-tap charge-coupled device (CCD) [5], complementary-metal-oxide-semiconductor (CMOS) transfer gates [6], demodulated photogates [7,9], and a pinned photodiode with transfer gates [8], or through resistive switching devices, such as a current assisted photonic demodulator (CAPD) [10-13]. To achieve a high signal-to-noise ratio and therefore a small depth error in an indirect TOF measurement, it is desired to increase the quantum efficiency and the frequency bandwidth of a lock-in pixel. With the recent trend to shift the near-infrared (NIR) operation wavelength from 850 nm to 940 nm to take advantage of the solar spectrum dip at 940 nm (i.e., operating at a low ambient-light induced noise condition to expand the user experience from indoor to outdoor scenarios), the quantum efficiency degrades further as Si features a weak absorption at a longer NIR wavelength. Limited by the efficiency-bandwidth-product, while it is possible to obtain a higher quantum efficiency by simply having a thicker Si absorption layer, the resultant smaller frequency bandwidth may in return further degrade depth accuracy. Consequently, it
has become more and more challenging to engineer a high-performing lock-in pixel.

In this work, we propose and demonstrate novel lock-in pixels for indirect TOF depth sensing and 3D imaging applications based on germanium (Ge)-on-Si technology. The Ge-on-Si technology [14] has been widely adopted for making optical receivers on Si photonics platform, especially for high-speed optical communication applications. Lateral p-i-n [15] and vertical p-i-n [16-19] photodiodes in normal-incidence configuration, as well as p-i-n [20-22,24] and metal-semiconductor-metal [23] photodiodes in waveguide configuration, have been previously demonstrated. Due to the lower bandgap of Ge compared to Si, Ge features a strong absorption at NIR wavelengths. When used in a lock-in pixel, such a property should boost the quantum efficiency and the frequency bandwidth, which may reduce the depth error measured in an indirect TOF system. Moreover, Ge-on-Si technology is CMOS fabrication process compatible, which may be incorporated into front-side illumination (FSI) and back-side illumination (BSI) CMOS image sensors in a straightforward manner.

The organization of this paper is arranged as below: in section 2, we layout the mathematical framework to analyze the system performance of an indirect TOF system; in section 3, we apply a finite-element approach to simulate the electrical-optical properties of a proposed Ge-on-Si lock-in pixel design; based on the numerical results, in section 4, we compare the system performance using either a conventional Si lock-in pixel or the proposed Ge-on-Si lock-in pixel; the electrical-optical characterization of the implemented Ge-on-Si lock-in pixels are then presented in section 5; finally, a summary is given in section 6.

2. Mathematical framework

Consider a two-tap lock-in pixel with a P1-Q1-Q2-P2 4-terminal configuration in which the input optical power and the photo-generated electrical current are sinusoidally modulated (with an infinite extinction ratio) and demodulated, respectively, at an operation frequency \( f_c \) with \( \phi_1 \) and \( \phi_2 \) initial phases, respectively. Then, the output electrical currents collected at the two P nodes with differential voltages applied to the two Q nodes can be expressed as

\[
I_x(t) = \left[ 1 \pm \frac{C_{Dx}}{2} \cos(2\pi f_c t - \phi_1) \right] \left[ I_{dc} + I_{ac}^p(f) \cos(2\pi f_c t - \phi_2) \right] + I_{dc}^t.
\]  

(1)

\( C_{Dx} \) is the direct-current (dc) demodulation contrast; \( I_{dc} \) and \( I_{ac} \) are the ambient and dark currents; \( I_{ac}^p(f) \) and \( I_{ac}^q(f) \) are the dc and alternating-current (ac) photo currents in which \( I_{ac}^p(0) = I_{ac}^p \). Physically, the differential voltages applied to the two Q nodes establish the designated electrical field distribution instantaneously, representing the first bracket in (1), and it requires some transit time for the photo-generated currents to be collected by the two P nodes, representing the second bracket in (1). The dark current, ambient current, and photo current are assumed to be caused by material defect, ambient light, and laser light, respectively. Now, the time-average output electrical currents with the photo current component included but with the ambient current and the dark current components excluded can be derived as

\[
\langle I_x \rangle = \frac{1}{2} I_{dc} + \frac{1}{4} C_{Dx} I_{ac}^p(f) \cos(\phi_1 - \phi_2),
\]

(2)

so if we define an “ac” demodulation contrast as

\[
C_{Dac}^p(f) = \frac{\langle I_x \rangle - \langle I_x \rangle_{\text{max e.g. } \phi_1, \phi_2 = 0}}{\langle I_x \rangle + \langle I_x \rangle_{\text{max e.g. } \phi_1, \phi_2 = 0}} = \frac{C_{Dx}}{2} \frac{I_{ac}^p(f)}{I_{dc}}
\]

(3)

and insert it into (2), we arrive at

\[
\langle I_x \rangle = \frac{1}{2} I_{dc} + \frac{1}{2} C_{Dac}^p(f) I_{dc}^t \cos(\phi_1 - \phi_2).
\]

(4)

By comparing (2) and (4), the concept of defining an “ac” demodulation contrast in (3) becomes clear, i.e., in a time-average sense, the transit time induced frequency response originally embedded in the second bracket in (1) is now effectively embedded in the first bracket in (1). Note that unlike the range of \( C_{Dac}^p(f) \) that is between 0–1, the range of \( C_{Dac}^p(f) \) is between 0–0.5.

The stored charge on one of the two floating-diffusion capacitors connected to the two P nodes over duration \( r \) can be then calculated by
\[
qN_z(\varphi_x, \varphi_y) = \lim_{\tau \to \infty} \int_0^{\tau} I_z(t) dt = \frac{1}{2} (2I^p + I^d) + \frac{1}{2} I^d \tau + \frac{1}{2} C_d^+ (f) I^d \tau \cos(\varphi_x - \varphi_y).
\]

By defining
\[
qN_z(\varphi_x, \varphi_y) \triangleq \frac{1}{2} qN_{dp} \pm \frac{1}{2} qN_p \cos(\varphi_x - \varphi_y)
\]
and
\[
qN_{iq} \triangleq qN_z(0, 0) - qN_z(0, \varphi)
\]
\[
qN_{iq} \triangleq qN_z(\varphi, 0) - qN_z(0, \varphi),
\]

it can be shown that the depth measured in the indirect TOF can be expressed as
\[
z = \frac{d_u \varphi}{2\pi} = \frac{c}{4\pi f_m} \tan^{-1}\left(\frac{N_d}{N_p}\right),
\]
and the error of the depth measured in the indirect TOF can be expressed as
\[
\Delta z = \frac{d_u \Delta \varphi}{2\pi} = \frac{c}{4\pi f_m} \frac{N_{dp}}{N_p},
\]
assuming the stored charges feature a Poisson distribution. \(d_u\) is the unambiguous range and is equal to \(c/2f_m\). The electron numbers associated with the dark current, ambient current, and photo current in (9) are \(2I^d/\varphi q\) (due to material defect), \(I^d/\varphi q\) (due to ambient light), and \(I^d/\varphi q\) (due to laser light), respectively, and will be denoted as \(C, B,\) and \(A\) in the following. Finally, we can re-write (9) as
\[
\Delta z = \frac{c}{4\pi f_m} \frac{1}{C_d^+ (f_m)} \frac{1}{A+B+C}.
\]

It can be seen from (10) that to have a small depth error, the quantum efficiency that is linearly proportional to \(A\) should be increased, and the frequency bandwidth of the ac demodulation contrast should be increased to allow a higher operation frequency. As will be elaborated in the next section, these properties make the proposed Ge-on-Si pixel a strong contender against the conventional Si pixel.

3. Device Simulation

We apply a two-dimensional (2D) finite-element approach to simulate the steady and transient states of the proposed Ge-on-Si pixel. A Ge layer is supported on a Si substrate, and the 4 terminals of the two-tap lock-in pixel are prepared in the order of P1-Q1-Q2-P2. As previously described, differential voltages are applied to the Q1 and Q2 nodes to act as two effective switches in “on-off” or “off-on” state, and steer the photo-generated currents to be collected ideally by either the P1 or P2 node. The Ge electron and hole mobilities are taken as 3900 and 1800 cm²/V/s, respectively. Note that additional dopants are introduced in Ge in order to mimic the lattice-mismatch induced charge defects when epitaxially growing Ge on Si substrate. Moreover, we apply a trap-assisted bulk Shockley-Read-Hall model and a surface recombination model to match the experimentally measured dark currents of the vertical p-i-n photodiode in Ref. [17]. The simulated Ge-on-Si pixel is arranged in a BSI configuration, i.e., the Ge layer on the Si substrate is flipped up-side-down and bonded to a carrier substrate, and then the Si substrate is grinded as a thin Si layer with an anti-reflection coating (ARC) applied to its backside. A 940 nm laser light of a finite size is injected from the backside of the Si layer, to mimic the effect of an aperture on the backside of the Si layer and sandwiched in between the two Q nodes. All simulations are done in an equilibrium environment of 300 K.

In Fig. 1(a), the simulated quantum efficiencies for the two P nodes are plotted as a function of the differential voltage applied to the two Q nodes. It can be seen that when the voltage applied to Q1 is higher than that applied to Q2, photo-generated carriers tend to be collected by P1, i.e., the two effective switches are in the “on-off” state, and vice-versa. The total quantum efficiency, which is the sum of the quantum efficiencies for the two P nodes, is as high as ~93 % regardless of the differential voltage bias condition. In Fig. 1(b), the simulated dc demodulation contrast is plotted as a function of the differential voltage applied to the two Q nodes. It can be seen that the dc demodulation contrast increases first linearly and then sub-linearly with the differential voltage applied. In Fig. 1(c), the simulated small-signal frequency response of the ac demodulation contrast is shown. Instead of applying a differential
voltage varying sinusoidally as a function of time to the two Q nodes and detecting the low-frequency signal amplitudes at the two P nodes, here we apply Eqn. (4) to calculate the small-signal response, i.e., by first preparing an input optical delta or step function, monitoring the “smeared” output electrical delta or step function, and then performing a fast Fourier transform of the “smeared” output electrical delta or step function with an appropriate re-normalization. It can be seen that the 0.5 dB and 3 dB frequency bandwidth of the proposed Ge-on-Si pixel are as large as ~412 MHz and >1GHz, respectively.

We have shown in Fig. 1 that the proposed Ge-on-Si pixel features a high quantum efficiency and a large frequency bandwidth compared to the conventional Si pixels [5-13]. Moreover, the proposed Ge-on-Si pixel is also suitable for operation with eye-safe lasers (wavelength > 1.4 μm) that mitigates risk of retina burn. This is of particular importance for consumer applications when a high depth accuracy is needed, e.g., indoor/outdoor navigations that typical requires a peak laser power of a few watts, as human eyes can be irreversibly damaged when exposed to such a peak laser power at 850/940 nm wavelengths. Shifting the operation wavelength from 850/940 nm to > 1.4 μm may also drastically increase the depth accuracy, as a much higher laser power can be applied yet still in compliance with eye-safety regulations. Note that while pixels made from some III-V semiconductor or organic material may also detect the eye-safe wavelengths, unlike these solutions, the proposed Ge-on-Si pixel may benefit from its compatibility with CMOS foundry process, which eases the complexity in integrating with electronic circuits and improves the fabrication yields. In Fig. 2, we re-simulate the quantum efficiencies, dc demodulation contrast, and ac demodulation contrast at 1550 nm wavelength as an example of applying an eye-safe laser. Note that the Ge-on-Si tensile strain induced enhancement of absorption coefficient at 1550 nm is assumed to be 3460 cm⁻¹ [16]. In Fig. 2(a), the total quantum efficiency is as high as ~ 43 % regardless of the differential voltage bias condition. Interestingly, in Fig. 2(b) and 2(c), we observed very similar results compared to Fig. 1(b) and 1(c).
4. System performance comparison

In the following, we calculate and compare the depth errors between the proposed Ge-on-Si pixel and a conventional Si pixel. For the Ge-on-Si pixel, the operation frequency, quantum efficiency, and ac demodulation contrast are given based on the simulation of an optimized device, in which a slightly lower quantum efficiency is traded for a slightly higher ac demodulation contrast. For the Si pixel, the operation frequency and ac demodulation contrast are given based on the experimental data shown in Ref. [13], and the quantum efficiency is estimated based on Ref. [25]. These parameters are listed in Table 1. The dark currents are estimated based on the experimental data shown in Ref. [15-24]. The outdoor ambient light spectral intensity at 940 nm is given based on the air mass (AM) 1.5 condition, and the ambient light spectral intensity of the indoor case is assumed to be 100 times smaller than that of the outdoor case.

In Fig. 3(a), we plot the depth errors of the Ge-on-Si and Si pixels as a function of depth, for both the indoor and outdoor cases, given laser power equal to 0.5 W. It is observed that, for the indoor case, the depth error of the Ge-on-Si pixel is consistently better than that of the Si pixel; for the outdoor case, again, the depth error of the Ge-on-Si pixel is consistently better than that of the Si pixel but at a larger scale. Moreover, for the Ge-on-Si pixel, the depth error of the indoor case increases by only a fraction when moving to the outdoor case; for the Si pixel, the depth error of the indoor case increases by almost an order of magnitude when moving to the outdoor case. In Fig. 3(b), we plot the depth errors of the Ge-on-Si and Si pixels as a function of laser power, for both the indoor and outdoor cases, given depth equal to 1 m. Similar trends as in Fig. 3(a) are observed. These results might be surprising as the dark current of the Ge-on-Si pixel is set to be several orders of magnitude larger than that of the Si pixel (nearly no changes to Fig. 3(a) and 3(b) even if a lower Si pixel dark current is set). The reason lies in that, in an indirect TOF system, the dominant system noise is in fact due to the indoor/outdoor ambient light and the laser light instead of the dark current for various depth sensing and 3D imaging applications. This is in sharp contrast to the earlier efforts in replacing indium-gallium-arsenide (InGaAs) with Ge-on-Si to make sensors used in the short wavelength infrared (SWIR) camera [26], in which the focus is weak light detection without any active NIR lighting so that the system noise is limited by the pixel dark current, but analogous to the recent efforts in replacing III-V compound semiconductors with Ge-on-Si to make
receivers used in high-speed optical communication [27], in which the system noise is limited by the input referred noise of a transimpedance amplifier (TIA) instead of the detector dark current.

| TABLE 1 | Parameters used for system performance comparison |
|---------|---------------------------------------------------|
|         | Si Pixel       | Ge-on-Si Pixel |
| Operation Frequency | 100 MHz | 300 MHz |
| Quantum Efficiency  | 20 %     | 90 %        |
| ac Demodulation Contrast at Operation Frequency | 0.425 | 0.45 |

Fig. 3. (a) Depth errors plotted as a function of depth given laser power equal to 0.5 W. (b) Depth errors plotted as a function of laser power given depth equal to 1 m. Both indoor/outdoor conditions are considered.

5. Electrical/optical characterization

The device is fabricated by first an epitaxial growth of Ge on a Si wafer, and then going through the front-end pixel formation, back-end pixel metallization, and finally wafer stacking processes. For dc measurements, the fabricated Ge-on-Si pixels are characterized via a collimator coupled to a wavelength-stabilized 940 nm laser source. For ac measurements, a pulse pattern generator is used to apply a modulated signal and differential signals to an electro-optical modulator for modulating the laser source and to a Ge-on-Si pixel for demodulating the photo-generated currents, respectively, with variable phase delays. In Fig. 4(a), we plot the measured along with the simulated quantum efficiencies as a function of the differential voltage applied to the two Q nodes of the Ge-on-Si pixel. Consider the fact that in the simulation we use a nearly perfect ARC of ~ 99 % transmission but in the experiment an ARC of ~ 93 % transmission is used, the corresponding absorptions of Ge are estimated to be 94 % and 85 %, respectively. Such a discrepancy may relate to the defect absorption and the optical scattering through the aperture. Moreover, we observe a slight asymmetry between the photo currents collected at the two P nodes of the Ge-on-Si pixel, which may relate to the fact that the collimator is not configured in a perfectly normal direction. In Fig. 4(b), the measured and the simulated dc demodulation contrasts are shown to match well except the slight asymmetry. In Fig. 4(c), the measured ac demodulation contrast is slightly better than the simulated ac demodulation contrast, which may relate to the uncertainty in setting the electron and hole mobilities in the simulations. Note that the measured ac demodulation contrast data points are normalized to the first data point, i.e., at 50 MHz, when they are plotted in Fig. 4(c).
Fig. 4. The simulated and measured (a) quantum efficiencies and (b) dc demodulation contrast plotted as a function of differential voltage. The simulated and measured (c) normalized small-signal ac demodulation contrast plotted as a function of frequency. All simulations and measurements are performed with a 940 nm laser light.

6. Summary

We propose and demonstrate the use of Ge-on-Si technology to create a novel lock-in pixel for indirect TOF depth sensing and three-dimensional imaging applications. A high quantum efficiency and a large frequency bandwidth are measured at 940 nm wavelength, which can be further optimized in the future. We also show through simulations that the proposed Ge-on-Si pixels are capable of working at 1550 nm wavelength, which may enable future adoptions of eye-safe lasers (wavelengths > 1.4 μm) that fall outside of the operation window of conventional Si pixels.

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