Analysis of the high-speed polysilicon photodetector in fully standard CMOS technology

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Abstract—

A high-performance lateral polysilicon photodiode was designed in standard 0.18 μm CMOS technology. The device has a frequency bandwidth far in the GHz range: the measured bandwidth of the poly photodiode was 6 GHz, which figure was limited by the measurement equipment. The high intrinsic (physical) bandwidth is due to a short excess carrier lifetime. The external (electrical) bandwidth is also high because of a very small parasitic capacitance (<0.1 pF). This is the best bandwidth performance among all reported diodes designed in a standard CMOS. The quantum efficiency of this poly photodiode is 0.2% due to the very small light sensitive diode volume. The diode active area is limited by a narrow depletion region and its depth by the technology.

I. Introduction

For medium and short distance communication, fiber-to-the-home, fiber-to-the-desk, or board-to-board connection, the optical receivers and transmitters should be inexpensive. The motivation and potential to produce high-speed optical receivers in CMOS technology has increased markedly as the speed of today's CMOS circuits is well in GHz range, making them viable candidates for gigabit rate optical communication. In order to keep the cost of the short-haul data communication system low, the overall CMOS optical receiver should be monolithically integrated.

In literature, a few papers discuss high-speed photodetectors made in polysilicon [8],[10]. However, this is the first time that a polysilicon photodiode is designed in standard CMOS technology and the advantages and drawbacks for possible implementation as a high-speed photodetector are discussed.

This paper is organized as follows. Section II presents theoretical analysis of the speed of polysilicon photodiodes under condition of low carrier transit time in comparison with its recombination lifetime. This condition is satisfied for all narrow depletion region diodes. Also the diffusion current outside the depletion region is analyzed in detail. Section III presents a a frequency characterization of the polysilicon photodiode. Time-domain measurement using a picosecond laser source are shown and discussed in Section IV. Section V presents the responsivity and quantum efficiency of the designed poly photodiode.

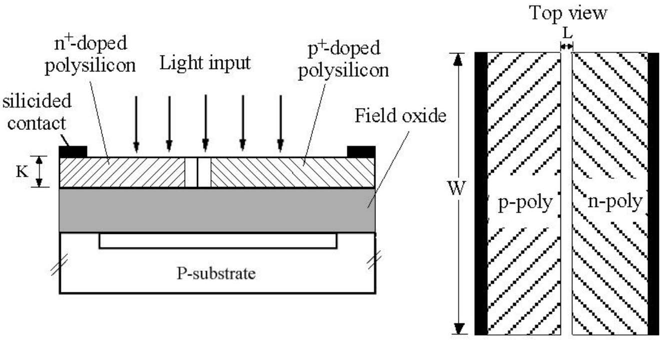

Fig. 1. Lateral polysilicon photodiode in CMOS technology

II. Polysilicon diode

In current MOS processes, polysilicon is used as a gate terminal for both NMOS and PMOS transistors. The lateral doping concentration of the polysilicon layer is high ($1 - 5 \cdot 10^{15}$ cm^{-2}) with the doping corresponding to the type of the MOS transistor. Using these two opposite types of poly layers, a p-n junction was fabricated; see Figure 1.

Figure 2 shows the diode I-V characteristic. The large leakage current is due to grain-boundary trap-assisted band-to-band tunnelling and field-enhanced emission [1].

During the chip processing it can happen that the masks for the $n+$ and $p+$ doping are not perfectly aligned. This might influence the size of effective width of polydiode depletion region. However, measurements on number of devices on the same wafer showed that the polydiode is almost misalignment insensitive. It is also important that the measured chips are exposed on the different reticles.

Carrier lifetime in polysilicon diode depends on cap-

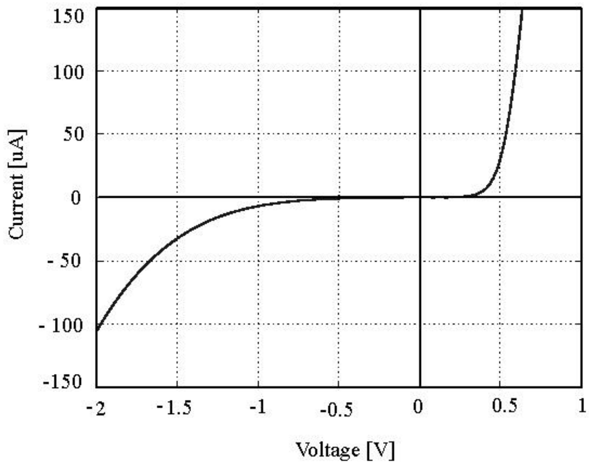

Fig. 2. Measured DC characteristics of "jagged" polysilicon photodiode in standard CMOS technology. The diode area was $45 \times 45\mu$m.

ture rates of holes and electrons as well as the concentration of grain boundary traps. Also, the electric field F acts on the trap capture probability [1]. In the space charge region, the electric field increases the carrier emission rate and the capture cross-section, so it decreases carrier lifetime. The carrier lifetime is inversely proportional to the grain size of polysilicon. In 0.18μm CMOS technology, the grain size is about 50-60nm [11], which causes the carrier lifetime to be very short, about $\tau_{n,p} = 50$ps [10]. Since in this case the diffusion speed of carriers is mainly determined by their lifetime, the diffusion bandwidth will be far in GHz range.

A. Pulse response of poly photodiode

The major speed limitation in all monosilicon photodiodes lies in the very slow diffusion of excess minority carriers generated deep into substrate when using long- wavelength light (λ=850nm) [3]. The speed of the photodetectors is however, generally limited by two mechanisms. One is the intrinsic (physical) photodiode speed determined by the physical carrier transit time and diffusion time inside the photodiode. The other one is the external (electrical) speed determined by a diode parasitic capacitance. The overall speed is by approximation the lowest of these two.

Further in this chapter, the intrinsic diode speed limitations will be investigated. The impulse response of poly photodiode including drift and diffusion of carriers inside depletion region and diffusion outside this region will be calculated. The later is not negligible for narrow poly photodiodes without the intrinsic region.

The transport of the carriers inside a polysilicon junction is described with drift-diffusion equations in [4],[6]. Since the depth of polysilicon layer K, is small in comparison with its width, a one-dimensional time-dependent drift-diffusion equation is solved. The charge carrier behavior in other dimensions is assumed constant. When the input light pulse is incident on the device, the generation rate $g(x,t)$ is:

$$g(x,t) = \Phi(1-R)[H(x) - H(x-L)]\frac{(1-e^{-\alpha K})}{K}\delta(t) \tag{1}$$

where Φ is the incident light flux, R is reflectivity of the surface, K is the depth of the polysilicon layer, α is absorption coefficient and H and δ are Heaviside and Dirac pulses, respectively.

The most elegant way to solve drift-differential equations is first to simplify them by two substitutions. The substitution $n(x,t) = \exp(-t/\tau_n)N(x,t)$ into the drift-diffusion equation in [5], where $/\tau_n$ is the electron recombination lifetime reduces the equation to:

$$\frac{\partial N(x,t)}{\partial t} = D_n\frac{\partial^2 N(x,t)}{\partial x^2} \pm v_n\frac{\partial N(x,t)}{\partial x} + g(t,x) \tag{2}$$

Then, substituting $\zeta = x \pm v_n\, t$ and $\theta = t$ into eq. (1), the following partial differential equation is obtained

$$\frac{\partial N(\xi,\theta)}{\partial \theta} = D_n\frac{\partial^2 N(\xi,\theta)}{\partial \zeta^2} + g(\zeta,\theta) \tag{3}$$

The above equation is well-know equation of thermal conduction [9] and the final solution (after restoring the variables) is:

$$\begin{aligned} n(x,t) =& \; \Phi(1-R)e^{-\dfrac{t}{\tau_n}}\frac{(1-e^{-\alpha K})}{K}H(t) \\ &\times\frac{1}{2}\left[\operatorname{erf}\left(\frac{L-x\mp v_n t}{2\sqrt{D_n t}}\right) + \operatorname{erf}\left(\frac{x \pm v_n t}{2\sqrt{D_n t}}\right)\right] \end{aligned} \tag{4}$$

A similar analytic expression follows for holes, by simply replacing $\pm v_n$ with $\mp v_p$ and D_n with D_p.

The associated photocurrent $i_1(t)$ can be obtained by volume integration [5] of the conduction current density which consists of the photo-generated carriers moving over the graded depletion region, and dividing the result by the depletion region width L :

$$i_1(t) = \frac{qW}{h\nu}(1-R)\frac{(1-e^{-\alpha K})}{K}\Phi H(t) \times \sum_{j=n,p} e^{-\frac{t}{\tau_j}}\left[E_1(t,v_j,D_j)+E_2(t,v_j,D_j)\right] \tag{5}$$

where W is the width of the poly photodiode. The functions $E_1(t,v_j,D_j)$ and $E_2(t,v_j,D_j)$ are defined in terms of error functions and exponential functions, respectively:

$$\begin{aligned} E_1(t,v_j,D_j) = \; & -(D_j+v_j^2t)\mathrm{erf}\left(\frac{v_jt}{2\sqrt{D_jt}}\right) \\ & -\frac{1}{2}\mathrm{erf}\left(\frac{L-v_jt}{2\sqrt{D_jt}}\right)\left[v_j^2t-v_jL+D_j\right] \\ & +\frac{1}{2}\mathrm{erf}\left(\frac{L+v_jt}{2\sqrt{D_jt}}\right)\left[v_j^2t+v_jL+D_j\right] \end{aligned} \tag{6}$$

$$\begin{aligned} E_2(t,v_j,D_j) = \; & \frac{v_j\sqrt{D_jt}}{\pi}\left[\exp(-\frac{(L-v_jt)^2}{4D_jt})\right. \\ & \left.+\exp(-\frac{(L+v_jt)^2}{4D_jt})-2\exp(-\frac{v_jt^2}{4D_jt})\right] \end{aligned} \tag{7}$$

When diffusion is negligible and excess carrier lifetime is longer than the carrier transit time (as is the case for CMOS poly-diodes without an intrinsic layer), the impulse response of the polysilicon diode can be simplified to:

$$i_1(t) = \frac{qW}{h\nu}\Phi(1-R)\frac{(1-e^{-\alpha K})}{K}\sum_{j=n,p} v_j(L-v_jt)H(L-v_jt) \tag{8}$$

The exponential term in the drift-diffusion equation 5 is taken to be equal to one. For polydiodes with large intrinsic layer, the recombination lifetime is much shorter than the transit time and the impulse response is given in [6].

B. Diffusion current outside the depletion region

If the polysilicon photodiode is realized using two highly (inversely) doped regions without an intrinsic layer in between, the width of depletion region is very small and diffusion current outside of this region will also contribute the overall photocurrent. This current is calculated in both diffusion layers by taking the excess carriers on the edge of depletion region to be zero [4]. The same boundary condition is taken also for the carriers on the diffusion distance $L_j,\ j=n,p$. From the calculated carrier profile, diffusion current can be further calculated at the border of the depletion region:

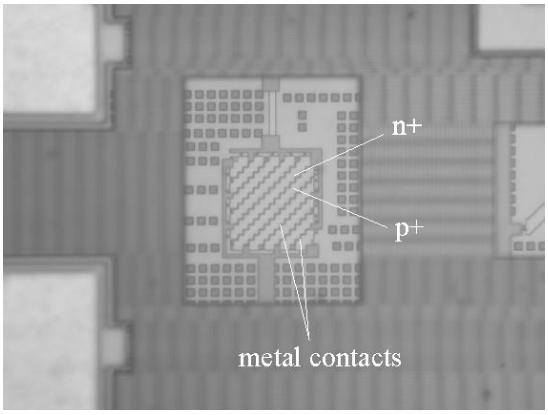

Fig. 3. Layout of "jagged" poly photodiode designed to increase the overall light sensitive area

$$i_2(t) = 4qWL\Phi\frac{1-e^{-\alpha K}}{K}\sum_m\sum_{j=n,p}\frac{L_j}{\tau_j}e^{-[(1+(2m-1)^2\pi^2]\frac{t}{\tau_j}} \tag{9}$$

Due to the exponential term in the equation 9, the speed of a diffusive response is mainly determined by the lifetime of the excess carriers. Noting this lifetime is short (ps), the response speed of diffusion current component will be in GHz range. The overall photocurrent is obtained as the sum of drift and diffusion current.

III. FREQUENCY CHARACTERIZATION OF POLYSILICON DIODE

The light sensitive part of a poly photodiode consist only of small depletion region area and the area outside this region proportional to a diffusion length of holes and electrons. This diffusion area is very small in comparison with that in a monosilicon diode (<0.1 μm). The depth of the polysilicon in standard CMOS technology is small, about 0.2μm and it also contributes to a poor responsivity of poly photodiode.

In order to increase an active photodiode area a "jagged" polysilicon diode consisting of a number of polydiodes connected in parallel was designed (Figure

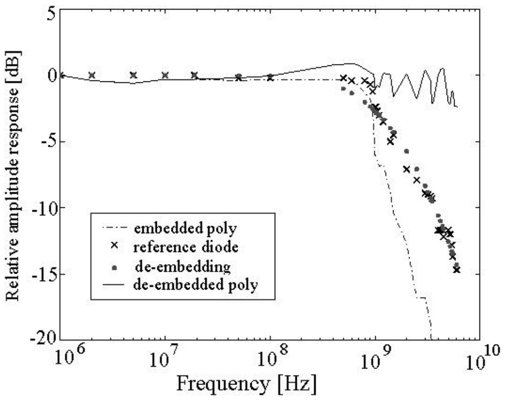

Fig. 4. Frequency response of de-embedded polysilicon photodiode

3.). The overall active area is about 13 times larger than that in the single polydiode. The measured output signal is however 17 dBm larger meaning that the expected depletion area increased less than proportional. This is due to rounding effects at the many corners in the poly p-n structure.

The frequency response of the photocurrent is measured using a Agilent E4404E Spectrum Analyzer. The response of polysilicon photodiode is measured from 1MHz up to 6GHz. This range is chosen for the reliable results of the measurement setup. For frequencies up to 1GHz, the signal from the photodiode was amplified using a Minicircuits ZFL 1000LN 0.1-1000 MHz amplifier. For frequencies above, we used 0.5-26.5 GHz Agilent 83017A Microwave system amplifier.

The transmitter part consist of the 850nm 10 Gb/s VCSEL and its driver amplifier. An HP 8665B frequency synthesizer was used as a modulating signal source up to 6 GHz. The signal was coupled into the photodiode using multimode fiber with 50μm core diameter.

The same setup, for calibration purpose, was used to measure a reference photodiode (Tektronix SA-42) response, which has according to a specifications, 7GHz-3dB frequency. The response of the reference diode in the setup is presented in Figure 4.

The polysilicon photodiode frequency characteristic was de-embedded out of the parasitic bondpad capacitance and parasitic capacitance of the picoprobes. The overall frequency characteristic is presented in Figure 4.

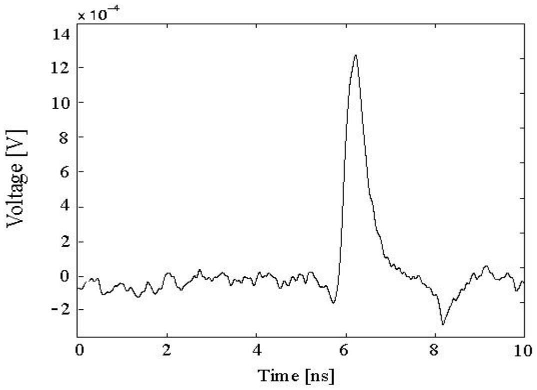

Fig. 5. Transient response of embedded poly photodiode on 300 ps input light pulse (transimedance 750 Ohm, $\lambda =$ 850nm).

IV. Time-measurements on polysilicon diode

Apart from the frequency characterization, also time-domain measurements on poly photodiode were performed.

A picosecond laser with $\lambda = 650$nm was used as a transmitter. The light was focused into a multimode fiber using a system of lenses. The pulse width of the picosecond laser is about 300 ps and the power of about 3mW. The output of the embedded poly photodiode signal is presented in Figure 5.

The Tektronix SA-42 photodetector is again used as a reference. The measured time response of this photodetector is presented in Figure 6.

In order to determine the speed of the response of de-embedded poly photodiode, the convolution between a reference diode signal and de-embedding of polysilicon photodiode is calculated and the result is shown in Figure 6. It is clear that the speed of de-embedded polysilicon photodiode is at least as fast as a reference opto-electrical converter which has 7GHz cutoff frequency.

V. Quantum efficiency and sensitivity

The quantum efficiency of the poly photodiode can easily be measured using a well known reference diode (PIN-HS040). The measured responsivity of the poly photodiode at 850nm is 1.20 mA/W which implies that a quantum efficiency is small $QE_{\text{meas}} \sim 0.2\%$.

Using simplified formula for the maximum achievable quantum efficiency $QE_{\text{max}} \sim 1 - e^{-\alpha K} = 6\%$, the effective (light sensitive) detector area A_{eff} is determined using following equation:

$$QE_{\text{meas}} = QE_{\text{max}} \frac{A_{\text{tot}}}{A_{\text{eff}}} \tag{10}$$

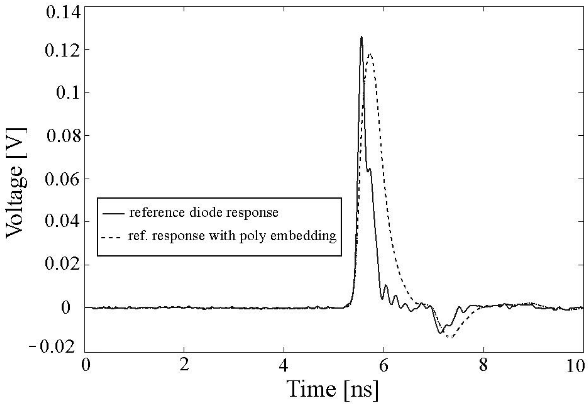

Fig. 6. Transient response of the reference photodiode (7GHz-3dB, transimedance 750 Ohm, $\lambda = 850$nm) and its convolution with the embedding of poly photodiode)

where A_{tot} is a total photodiode area. Its value is only 3% implying very thin depletion regions as well as small diffusion area outside it.

VI. CONCLUSION

A lateral polysilicon photodiode in standard CMOS technology is designed and implemented as a high-speed photodetector. Both frequency and time measurements showed that polysilicon photodiode has very fast response $f_{3dB} > 6$GHz.

The frequency bandwidth of poly diode is determined by both intrinsic (physical) diode bandwidth limited by finite speed of the carriers and external (electrical) bandwidth determined by diode parasitic capacitance. Due to a small excess carrier lifetime, the slow diffusion limitation on the intrinsic (physical) polydiode bandwidth is negligible. The electric bandwidth limitation is also minimal because of the small diode parasitic capacitance proportional to a low depth of polysilicon layer.

The disadvantage of the polydiode is the low quantum efficiency. This is because of a very thin light sensitive area: the width of depletion region is small because of the absence of an intrinsic layer while the depth is limited by the technology. The quantum efficiency can be improved using three different methods. First, it is increased by building the light reflectors i.e. design a resonant-cavity photodiode [10]. This is however not available in standard CMOS technology. Second method is to use low wavelength high-frequency light source ($\lambda = 500 - 600$nm). The third method is to design of PIN poly photodiode: during the manufacturing process, the option of non-doping polysilicon layer existence should be allowed.

VII. **Acknowledgments**

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