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Modelling, design and characterization of Schottky diodes in 28nm bulk CMOS for 850/1310/1550nm fully integrated optical receivers

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Abstract—This paper presents N-well Schottky diodes for high speed optical detection in 28nm CMOS technology. These diodes enable fully integrated CMOS optical receivers suited for the 850, 1310 and 1550nm telecommunication bands. The measured 1310 and 1550nm DC responsivity is 0.71mA/W and 0.16mA/W respectively at 1.5V reverse bias when backside illumination is performed while the 850nm responsivity is 0.27mA/W at the same biasing when frontside illumination is done. This is the first reported CMOS photodetector demonstrated at these three wavelengths. The measured capacitance-to-area ratio at zero bias is 1.7mF/m².

I. INTRODUCTION

Glass fiber-optic communication links have nearly unrivalled performance concerning data rates and distance. These links generally make use of 1310 and 1550nm light through a single-mode fiber (SMF) or 850nm light through a multi-mode fiber (MMF). At the receiving end, the optical receiver typically consists of a high-speed photodetector to convert the optical signal into an electrical current, a transimpedance amplifier (TIA) to convert this current into a voltage and a post-amplifier to amplify this voltage to rail-to-rail levels [1]. As the photodetector is the first block of the receiver, its performance largely determines the overall performance of the full receiver.

For high-end receivers, each of these blocks is typically implemented on a separate chip in a different technology. The photodetectors of these systems are either PiN- or avalanche photodiodes. These diodes are fabricated in dedicated technologies to obtain high responsivity, high bandwidth and low capacitance for low dark currents. While these receivers have excellent performance, this multi-chip implementation and the resulting stringent packaging requirements result in a high cost. On the other hand, Photonic integrated circuits (PICs), keep gaining more attention [2], since these technologies enable integrating optical components, such as lasers, electro-optical modulators and photodetectors, on a single die. However, while CMOS-integrated photonics technologies have been demonstrated [3], most of them make use of relatively old CMOS technologies. Furthermore there is a lack of standardization.

Optical receivers can also be monolithically integrated in (modern) CMOS technologies. However, because there is barely any light absorption in silicon for wavelengths longer

than 1.1 μ m, nearly all research has been aimed at 850nm receivers. As PiN-photodiodes are not available in standard CMOS technologies, the reported optical receivers make use of PN-diodes, some in the linear region [4], [5], others in the avalanche region [6]. P-substrate/N-well junctions provide the largest space charge region (SCR) and smallest capacitance and are thus the preferred choice for photodiodes in the linear region. Although the DC responsivity for 850nm light is relatively high, the low absorption coefficient of silicon results in a low photocurrent bandwidth (1-10MHz) because of carriers generated deep in the substrate [7]. An additional equalizer is necessary to compensate for this intrinsic low bandwidth. Alternatively, spatially modulated light (SML) photodiodes provide bandwidth extension at the cost of reduced responsivity, but ultimately degrade the signal-to-noise ratio (SNR) since half of the light is reflected by the metal coverage. When the reverse bias voltage is increased to high voltages, PN-junctions go into avalanche region. Operation in this region leads to increased responsivity and bandwidth, but also to larger photodiode noise. As junctions with thin avalanche regions result in the lowest excess noise factor [8], P+/N-well/(P-substrate) junctions are the preferred choice for avalanche photodiodes in CMOS.

As mentioned, PN-photodiode-based receivers in CMOS are only suited for short wavelength links (660nm in plastic optical fiber or 850nm in multi-mode fiber). There are thus no CMOS receivers reported for 1310/1550nm SMF links, which are traditionally used for long-haul communication. In [9], N- and P-well Schottky diodes in 40nm CMOS are presented, which can convert 1310nm light through internal photoemission (IPE). These devices are however not optimized for fiber coupled receivers: the large rectangular shape leads to excessive and unnecessary capacitance, while the distributed layout leads to a low diode fill factor, which results in a low responsivity. In this work, two circular plain layout N-well Schottky photodiodes in 28nm CMOS are presented. Their sizes are matched to a SMF and a MMF.

This paper is structured as follows. Section II gives some insight of the mechanisms of Schottky photodiodes, as well as design and layout considerations. In Section III, the I-V, capacitance and responsivity measurement results of the diodes are presented while comparing them to the N-well diode in [9]. Finally, Section IV gives a conclusion.

II. CMOS SCHOTTKY DIODES

Fig. 1: Zoomed-in photograph of the presented 28nm Schottky diodes. The diode on the left is matched to a MMF, the diode on the right to a SMF.

A photograph of the presented diodes can be seen in Fig. 1. In Fig. 2, the working principle of internal photoemission (IPE) for an N-type Schottky diode can be seen. The light gets absorbed in the metal and if the excited electron has sufficient energy, it can cross the Schottky barrier ϕ_B . The maximum detectable wavelength is thus given by $hc/q\phi_B$, where h is Planck's constant, c is the speed of light and q is the elementary charge. This implies 1550nm and 1310nm can be detected for a Schottky barrier of 0.8eV and 0.95eV respectively. The quantum efficiency (QE) is however rather low, since the metal reflects most of the light. The closer the photons are absorbed to the barrier, the higher the probability to cross the barrier. The QE also increases for bigger energy differences between photon energy and ϕ_B [10].

Fig. 2: The principle of internal photoemission: a photon gets absorbed in the metal, exciting an electron to a higher energy level in the process. If the electron has gained sufficient energy, it can cross the Schottky barrier ϕ_B .

A topside and cross section view of the presented diodes can be seen in Fig. 3. Schottky diodes can be realized in CMOS by placing contacts to the relatively lowly doped N-well. A wide junction is formed between the silicon and the silicide. Ohmic contacts to the highly doped N+ layer make up the cathode of the device. Both diodes are circular and have a diameter of 51.3 μ m and 9 μ m. These dimensions are chosen as to be matched to MMFs and SMFs, of which the core typically has a diameter of 50-62.5 μ m and 8-10 μ m respectively. Light can be impinged from the top (frontside illumination - FSI)

or from the back (backside illumination - BSI). FSI can be performed for the three telecom wavelengths, but only 1310nm and 1550nm can be impinged from the backside due to the non-transparency of silicon for 850nm light. When the chip is illuminated from the top, the photons get absorbed at the top of the M1 layer. The excited electrons must then travel a relatively large distance without losing energy in order to cross the barrier. The probability of these electrons crossing the barrier is much lower than those generated close to the junction, as is the case for BSI. Because of this, BSI results in larger responsivity than FSI. The intrinsic bandwidth of IPE-based photocurrent can easily be in the GHz range: unlike 850nm FSI for CMOS PN-diodes, all carriers are generated very locally and the intrinsic bandwidth is determined by the short transit time to cross the SCR.

Fig. 3: (a) topside view - red region denotes Schottky regions, green region Ohmic regions (b) cross-section view - silicide and N-well silicon form Schottky region, silicide and N+ region form Ohmic region

The chosen layout maximizes the realizable diode area and responsivity. Whereas the silicide and M1 layers make up the entire area, technology design rules limit the contact width and spacing, resulting in a maximum 10% of the device area covered with contacts. Unlike the diodes in [9], the Schottky photodiodes in this work do not have metal dummies on top of them, which means FSI can be performed on them. This opens up the possibility of 850nm detection.

III. MEASUREMENTS

No standard CMOS process is intended to realize Schottky diodes and thus no model is available. Therefore, the performance of the Schottky diodes is first characterized, after which an analog front-end can be designed. The equivalent schematic of the Schottky photodiode can be seen in Fig. 4. The actual junction can be represented by a voltage dependent resistor r_d , a voltage dependent junction capacitance C_d and a photosensitive current source I_{ph} . The series resistance R_s represents the path from the cathode to the junction.

Fig. 4: Schottky photodiode equivalent schematic

A. I-V characteristics

The current-to-voltage characteristics without illumination of the devices, measured using a Keithley 2600 SMU, are shown in Fig. 5. Four important properties can be extracted from these dark current curves: the noise, the junction small-signal resistance r_d , the series resistance R_s and the Schottky barrier ϕ_B .

The diode noise is dominated by the shot noise. An expression is given by (1), where I_{ph} is the DC photocurrent, I_{dark} is the DC dark current and BW is the extrinsic bandwidth of the diode.

$$I_n = \sqrt{2q(I_{ph} + I_{dark})BW} \quad (1)$$

As can be seen, the dark current of the two diodes is not larger than a few nA, suggesting a high Schottky barrier. The integrated shot noise current for 1nA dark current, 500nA photocurrent and 10GHz bandwidth is 40nA. As the input-referred noise current of a typical TIA at this bandwidth is much larger [5], this shot noise is of no further concern. The diode small-signal resistance for reverse bias voltages ranges between 0.1-1G Ω .

The I-V characteristics on a linear scale reveal the series resistance of the MMF and SMF diodes. They are 53 Ω and 102 Ω respectively. Despite the smaller device size, the series resistance of the SMF diode is larger than that of the MMF diode. This is due to the smaller spacing of the shallow trench isolation (STI), leaving a narrower path for the electrons to traverse. This series resistance due to STI could be minimized by adapting a poly-gate separated layout as in [11]. Finally, thermionic current theory [10] reveals a zero-bias Schottky barrier ϕ_B of 0.7eV. In comparison with the N-well diode in [9], which has a zero-bias Schottky barrier of 0.55eV, these diodes have a higher Schottky barrier, which results in a lower current. However, as shown in the next subsection, this also results in a lower responsivity.

B. Light responsivity

FSI was performed on a wire bonded chip with 850, 1310 and 1550nm light. The resulting responsivities at different biasing voltages can be seen in Fig. 6. As predicted in section II, the reponsivity increases for shorter wavelengths. The responsivity also increases for increasing reverse bias voltages

Fig. 5: IV-characteristics plotted (a) linearly (b) logarithmically

due to the barrier lowering effect [10]. At 1.5V reverse bias, the diodes have a responsivity of 0.27mA/W, 5.8 μ A/W and 1.1 μ A/W for 850, 1310 and 1550nm light respectively.

For the BSI measurements, a chip was mounted on a PCB by making use of flip-chip bonding. This time, only the responsivities for 1310 and 1550nm light were measured. They are shown in Fig. 7. At 1.5 reverse bias, the diodes have a responsivity of 0.71mA/W and 0.16mA/W for 1310 and 1550nm light respectively. Although the fill factor of these diodes is much bigger (3.5x for diode junctions, 2.7x for contacts) than that of the diode in [9], the BSI 1310nm responsivity is only 1.7x times larger. This can again be explained by the higher Schottky barrier in this technology.

Fig. 6: Schottky photodiode responsivity for FSI with different wavelengths

Fig. 7: Schottky photodiode responsivity for BSI with different wavelengths

C. Capacitance extraction

The diode small-signal impedance consists of r_d in parallel with C_d . From a certain frequency on, the junction impedance is dominated by the junction capacitance. This small-signal impedance can be obtained through s-parameter measurements. The measurements were performed with a HP 8573V VNA. The resulting impedances and capacitances can be seen in Fig. 8.

Fig. 8: (a) Diode impedances extracted from s-parameter measurements for different biasing voltages. (b) Diode junction capacitances for different biasing voltages.

The SMF diode has a capacitance of 175-125fF for reverse biasing voltages of 0-1.5V, while the MMF diode junction capacitance ranges between 3.5-2pF for the same biasing

Spec	40nm N-well diode [9]	28nm N-well diode
Schottky Barrier [eV]	0.55	0.7
Built-in Potential [V]	0.65	0.69
C/A [mF/m^2]	4.8	1.7
850nm Resp. [A/W]	N/A	$0.27\text{e-}3$ (FSI)
1310nm Resp. [A/W]	$0.4\text{e-}3$ (BSI)	$5.8\text{e-}6$ (FSI), $0.71\text{e-}3$ (BSI)
1550nm Resp. [A/W]	N/A	$1.1\text{e-}6$ (FSI), $0.16\text{e-}3$ (BSI)

TABLE I: Summary measurements results

voltages. This capacitance-to-voltage relationship reveals that the built-in potential of the Schottky diode is 0.69V. At zero bias, Schottky diodes in this technology have a capacitance-to-area ratio of $1.7\text{mF}/\text{m}^2$, whereas the diodes in [9] processed in 40nm CMOS have a ratio of $4.8\text{mF}/\text{m}^2$. As the built-in potential of that diode is 0.65V, this capacitance-to-area ratio also implies the N-well doping in that technology is higher. While Schottky diodes in this technology achieve a lower responsivity due to the higher Schottky barrier, the lower capacitance in turn relaxes the specs of the analog front-end [4]. The measurement results are summarized in TABLE I.

IV. CONCLUSION

N-well Schottky diodes in standard 28nm CMOS technology have been presented. These diodes can convert a very large spectrum of light to electric current at a large intrinsic bandwidth. Measurement results of I-V characteristics, capacitance and DC responsivity of 850, 1310 and 1550nm light have been shown. This is the first reported 1550nm responsivity of a CMOS photodetector. In comparison to N-well Schottky diodes in 40nm CMOS technology, the diodes in this technology achieve lower responsivity due to a higher Schottky barrier, but a lower capacitance-to-area ratio.

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