AC/DC Ratio Enhancement in Photoplethysmography Using a Pinned Photodiode

Antonino Caizzone, *Member, IEEE*, Assim Boukhayma, *Member, IEEE*, and Christian Enz, *Fellow, IEEE*

***Abstract*— Photoplethysmography (PPG) enables non-invasive vitals monitoring. Nevertheless, it is intrinsically limited by the extremely small AC/DC ratio, also called perfusion-index (PI). This increases the dynamic-range requirements to reliably process the PPG wave, particularly for applications requiring stricter specifications and lower noise. We present a PI-enhancement technique exploiting a double transfer gate (TG) pinned-photodiode (PPD) structure. The process takes place at the device level by optimizing the TG control voltage and transfer time. Measurement results show that the PPG PI can be enhanced by a factor 5 by choosing the optimal parameters and without any circuit overhead.**

***Index Terms*— PPG, perfusion-index, pinned-photodiode, dynamic-range.**

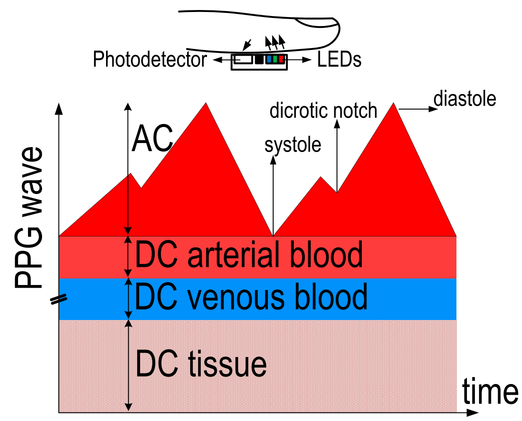

Fig. 1. Sensor set-up for a PPG measurement and the DC and AC components of a PPG signal.

I. Introduction

PHOTOPLETHYSMOGRAPHY (PPG) is a key technology allowing non-invasive monitoring of crucial vital indicators such as the heart rate (HR), the oxygen saturation (S_pO_2) and the blood pressure. As shown in Fig. 1, a PPG signal is obtained by shining light from an LED at a given wavelength, both visible and infrared, into an human tissue, e.g. finger, forehead, ear lobs. A photodetector (PD) detects the light transmitted through or reflected from the tissue and transforms it into a photogenerated current. The detected signal, i.e. PPG, consists of two different components: a large DC (quasi-static) component corresponding to the light diffusion through tissues and non-pulsatile blood layers, and a small AC (pulsatile) part due to the diffusion through the arterial blood. The AC component is only a small fraction (typically below 10%) of the DC one, depending on the body location and the skin tone [1]. Such small AC/DC ratio is called the perfusion-index (PI).

Due to the extremely low PI, dynamic-range (DR) is a key constraint in PPG sensors design. For instance, the DR ultimately determines the resolution with which S_pO_2 can be measured. The work in [2] shows the tight link between the required DR, the S_pO_2 and the *PI*. For the worst *PI* case, i.e. 0.2%, a receiver DR larger than 100dB is needed to ensure an accuracy within 0.2% of the S_pO_2 in the 70%-100% range.

State-of-the-art works have tried to solve the DR challenge in PPG analog front-end (AFE) either by the means of logarithmic amplifiers [3] or thanks to feedback loops which subtract a variable DC current from the AFE input [2], [4]–[6]. All the above-mentioned solutions rely on additional circuitry at the cost of more complexity, power consumption and silicon area. Another possibility relies on increasing the PD to LED distance, at the cost of a larger LED power [1].

The recent work in [7] shows an extremely low-power PPG sensor taking advantage of the high sensitivity of pinned-photodiodes (PPDs) together with an ultra-low noise and low power AFE. Moreover, the PD area is implemented as an array of double transfer-gates (TG) PPDs. The double TGs allows to precisely control the integrated charges and to efficiently cancel the ambient light (AL).

In this work, the double TG structure mentioned above is exploited to enhance the PI of the PPG signal at the device level consequently relaxing the DR requirements. Measurement results show that by tuning the TG control voltage and the transfer time, the PPG PI can be enhanced by a factor 5 without any signal loss or additional circuitry.

The letter is organized as follows: Section II describes the double TG PPD device and its operation that leads to the PI enhancement. Section III and Section IV present the

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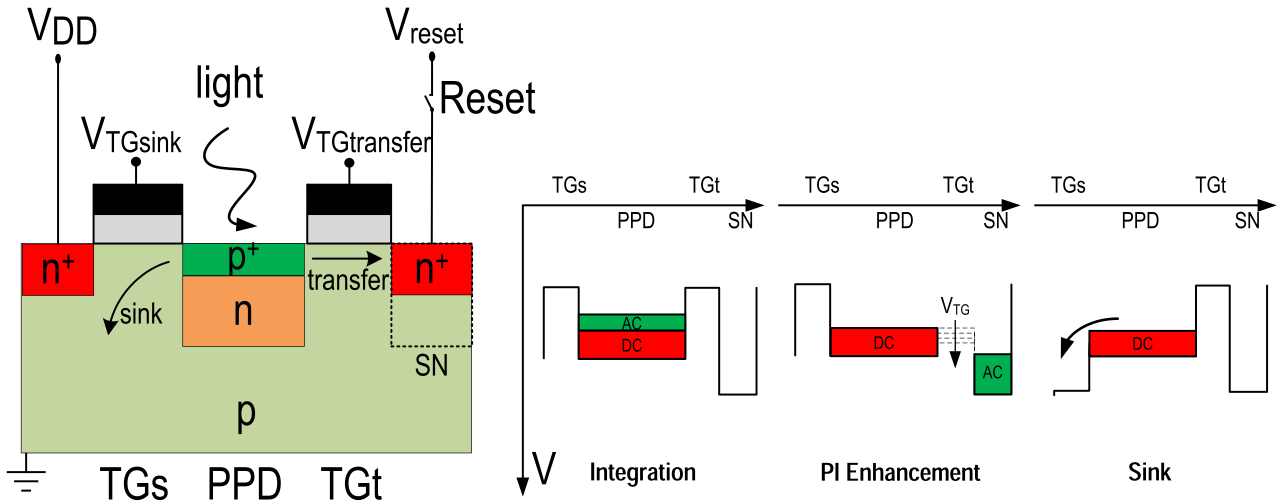

Fig. 2. The double TG PPD device and the three most important phases: integration, PI Enhancement and Sink. The PI Enhancement illustrates a PPD read-out in which only a part of the integrated photo-generated electrons reaches the SN.

measurement results and a deeper discussion on the reported results, respectively. Section V concludes the letter.

II. Device and Working Principle

A PPD consists of a np junction buried under a shallow highly doped p+ thin layer, as shown in Fig. 2. It behaves as a charge well where the photo-generated electrons are stored. The TG controls the potential barrier at the edge of the PPD. As shown in Fig. 2, the device is made of two transfer-gates, a sink transfer gate (TGs) and a transfer gate (TGt). This allows to precisely control the charge integrated into the well and eventually reaching the sense-node (SN). TGt allows only the part of the charge corresponding to the AC component of the PPG signal to reach the SN, whereas TGs dumps the remaining DC charge.

The work in [8] shows that the potential barrier encountered by the photo-generated electrons while diffusing towards the SN is modulated by the TG control voltage, V_{TG}. The amount of diffusing charge depends exponentially on V_{TG}, while logarithmically on the transfer time, $t_{transfer}$. Hence, V_{TG} and $t_{transfer}$ can be used to set the proportion of the diffusing charge towards the SN with respect to the one remaining in the PPD. This mechanism can be efficiently exploited to improve the PI of the PPG signal. Indeed, during the integration phase, assuming the PPD is far from saturation, the PPD stores both the DC and AC components of the PPG wave, as shown in Fig. 2. By tuning both V_{TG} and $t_{transfer}$, the PI can be enhanced by transferring only the AC-related charge, leaving the DC part in the well. The double TG scheme enables, thanks to the sink phase, to empty the PPD well from this remaining DC-related charge. Transferring only the AC-related charge to the SN relaxes the DR constraints on the AFE and reduces its power consumption.

III. Measurements Results

The idea described above is validated using the PPG sensor described in [7], which is fabricated in a standard 180nm CMOS Image Sensor (CIS) process. The PPG signal is emulated by a green LED shining at 525nm which is continuously driven by a sinusoidal current oscillating at 0.8Hz (corresponding to an HR of 48bpm), superimposed onto a DC current in order to mimic a PPG wave featuring a PI equal to 10%. It should be mentioned that the proposed method works throughout the full possible PPG frequency range (up to 4Hz), as long as the PPD integration time remains shorter than the maximum frame rate. The green LED is chosen since usually preferred in a PPG sensor for its intrinsic larger PI, as shown in [9]. On the other hand, the proposed method can be implemented even for different emitting wavelengths, i.e. red. The measures have been performed at 50Hz sampling frequency. The proposed set-up guarantees no artefacts coming from measurements on human beings. Indeed, factors such as the displacement between the body location and the PPG sensor or specific metabolic conditions may have introduced incoherent measurement results.

The measurement results are shown in Figs. 3 to 5. Fig. 3 shows the transferred DC and AC components of the emulated PPG signal versus V_{TG}, ranging from 0.3V to 3V and for different $t_{transfer}$, ranging between 100ns and 1 μs, at steps of 100ns. In Fig. 3 the trade-off between V_{TG} and $t_{transfer}$ is illustrated. For the longest $t_{transfer}$ equal to 1 μs almost all the DC charge is transferred for V_{TG} larger than 2.5V. Whereas, for the shortest $t_{transfer}$ equal to 100ns only 80% of the DC charge is transferred even at the maximum V_{TG}. Regarding the AC component, as expected, the full scale of the AC signal is roughly 10% of the DC one. Unlike the DC component, a complete AC transfer already happens at V_{TG} equal to 2V for the longest $t_{transfer}$. Fig. 3 illustrates that transferring the same fraction of charges requires less V_{TG} for the AC component than the DC one. This property can be exploited to enhance the PI of the PPG signal as demonstrated in Fig. 4. Fig. 4 shows the PI computed from the measured signals of Fig. 3 versus V_{TG}, for the same values of $t_{transfer}$. For all the proposed $t_{transfer}$, reducing V_{TG} down to a certain value comes with a significant increase in the measured PI, as explained above. A maximum PI has been measured between 0.75V and 1V. Below these values, the increasing potential barrier encountered by the photo-generated electrons comes with a consistent PI reduction. In addition to V_{TG}, $t_{transfer}$ represents a second degree of freedom. Indeed, Fig. 4 also shows that even for the optimal

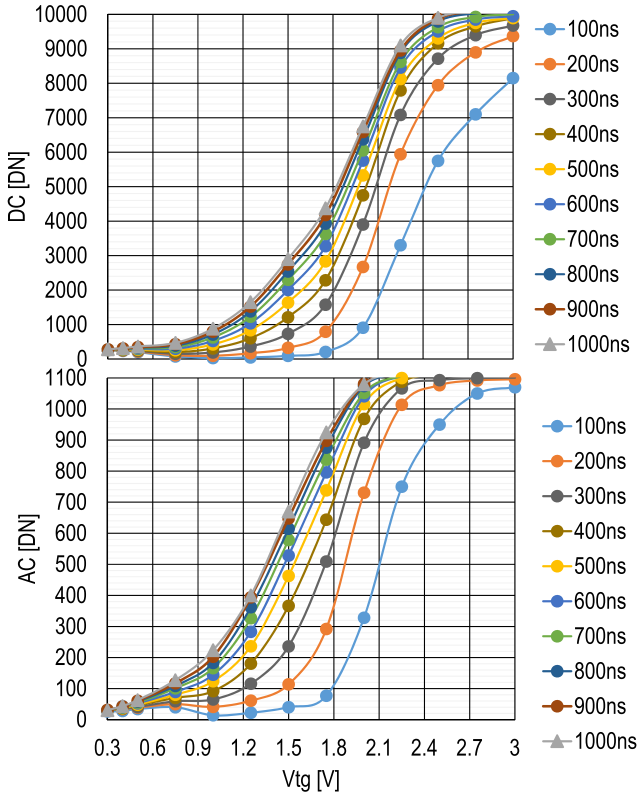

Fig. 3. Measured DC and AC components of the emulated PPG wave vs the TG control voltage for several transfer times.

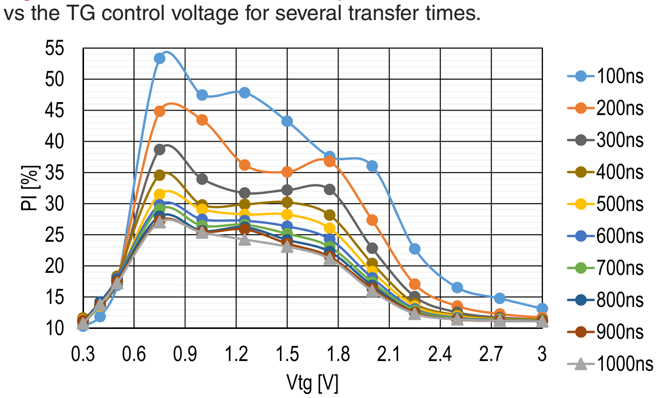

Fig. 4. Measured PI vs the TG control voltage for several transfer times.

V_{TG}, as above, shortening the transfer time is beneficial to enhance the PI. In particular, $t_{transfer}$ and V_{TG} equal to 100ns and 0.75V, respectively, show the best measured PI. Unlike the standard way of operating a PPD, $t_{transfer}$ and V_{TG} larger than 1 μs and 2.75V, respectively, the proposed configuration enhances the PI by more than a factor 5. Fig. 5 shows the impact of the proposed PI enhancement technique for three different emulated PI cases, 10%, 5% and 1% for $t_{transfer}$ of 100ns. It confirms that this technique can adapt to PPG signals with different PIs.

IV. Discussion

As shown in Fig. 3, thanks to the PI enhancement, the DC component drops from 10kDN to 80DN. This relaxes the DR constraints on the readout chain by 42dB. On the other hand, the AC component is also reduced. Hence, analysing the effect of the proposed PI enhancement technique on the signal-to-noise ratio (SNR) is also important. In PPG applications the best achievable SNR is limited by the shot noise related

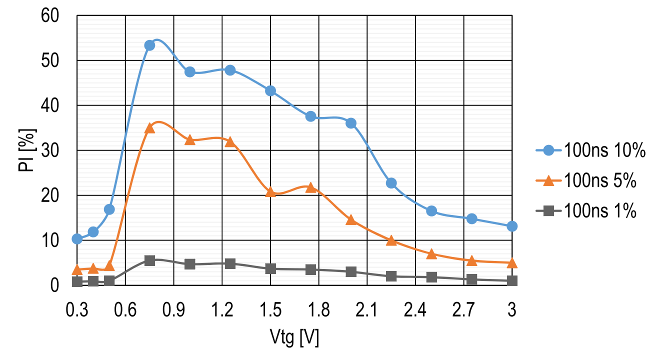

Fig. 5. Measured PI vs the TG control voltage at three different emulated PPG PI, 10%, 5% and 1%, for $t_{transfer}$ of 100ns.

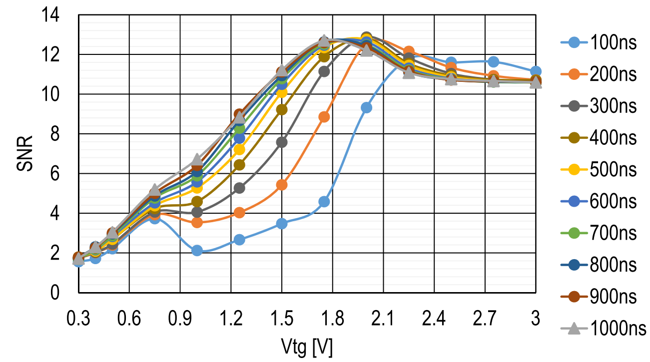

Fig. 6. Measured SNR vs the TG control voltage for several transfer times.

to the charge transfer mechanism, whose standard deviation corresponds to $\sqrt{DC + AC}$. The maximum SNR can then be expressed as $AC/\sqrt{DC + AC}$. Fig. 6 shows the impact of the PI enhancement technique on the SNR. For the 100ns $t_{transfer}$ case, the SNR can be maintained constant up to V_{TG} equal to 2.1V. In this case, for the same SNR, the DR is relaxed by more than 15dB.

V. Conclusion

This work illustrates the trade-off between the two readout parameters, namely the TG control voltage and the charge transfer time. It points out that a larger fraction of the AC signal is transferred at a lower TG control voltage with respect to the DC one. This translates into a maximum PI occurring at TG control voltage around 1V, for charge transfer time ranging between 100ns and 1 μs. A maximum PI enhancement of a factor 5 is reached for TG control voltage and charge transfer time equal to 1V and 100ns, respectively. In addition, the PI can also be increased considerably without any inpact on the SNR for optimal transfer parameters. Compared to state-of-the-art PI enhancement techniques, this work comes without any circuit power consumption or silicon area overhead. Indeed, the PPG PI is corrected right at the level of the PPD by properly tuning the TG control voltage and the charge transfer time. This last feature makes this solution particularly efficient for wearable health monitoring devices, especially when the body location or the skin tone make the PPG recording suffering from a particularly low PI.

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