WHITE PAPER :

HIGH-PERFORMANCE PHOTODIODES FOR WEARABLE HEALTH MONITORING

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ABSTRACT

Wearable healthcare technology has gained widespread popularity, both in clinical settings and daily health monitoring. ElFys introduces an advancement in this field with high-performance photodiodes (PDs) utilizing Black Silicon Induced Junction technology, aiming to enhance the accuracy and efficiency of wearable health monitoring devices, particularly in photoplethysmography (PPG).

Key Points:

- Wearable health technology is integral for continuous monitoring in clinical and daily contexts.
- ElFys addresses the demand for high accuracy , portability, and energy efficiency in wearable health monitors.
- Photoplethysmography (PPG) is a central technique, providing optical insights into changes in blood volume for heart rate and blood oxygen assessments.
- ElFys' Black Silicon Induced Junction PDs stand out for their effectiveness in measurement accuracy, power efficiency, and overall functionality.
- The innovative technology eliminates optical losses and ultilizies a recombination-free p-n junction, achieving near-ideal external quantum efficiency (EQE) across the UV-VIS-NIR spectrum.
- The SM series PDs from ElFys, designed for wearable health monitoring, exhibit exceptional sensitivity with significant improvements in photoresponse for green and red light.
- The benefits include a higher signal-to-noise ratio, enhanced accuracy, reduced power consumption, and the potential for designing smaller and more discreet wearables.
- The end-user experience is prioritized, offering potential for precise medical diagnoses, early disease detection, and effective sports training.

ElFys Black Silicon Induced Junction technology represents a significant advancement in wearable health monitoring, promising improved accuracy, sensitivity, and user-centric benefits, aligning with the evolving landscape of health and wellness technology.

About the Author:

Toni Pasanen works at ElFys, Inc. as a Senior Project Engineer and is one of the co-founders of the company.

He holds a D.Sc. (Tech.) degree in Micro- and Nanosciences from Aalto University, Finland, and has a background in applied research on semiconductor-based optoelectronic devices. He has several years of experience in the design and fabrication of various types of light and radiation detectors, as well as strong expertise on nanostructured black silicon surfaces and thin films. Dr. Pasanen has authored tens of peer-reviewed scientific articles, written a book chapter about the properties and applications of black silicon, and presented his work in several international conferences and other events.

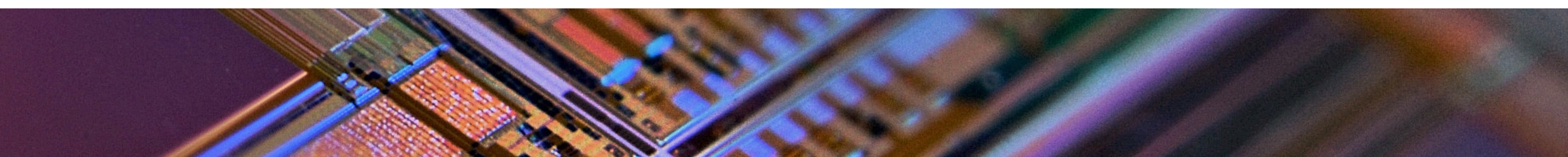
INTRODUCTION

Wearable healthcare technology is increasingly widely used in both clinical settings and everyday health monitoring. The technology offers several benefits for medical use. First, wearables enable continuous monitoring of vital body parameters, such as heart rate (HR) and blood oxygenation, also when the wearer is moving. This is important since it is essential for fast recovery that the patient can get up from the bed and start moving at the clinic as soon as possible, e.g., after surgery. Another reason for the widespread use of wearable technology is the simplicity and non-invasive nature of the measurements as they are often based on optical techniques. The devices are also lightweight and portable, and the patient can often perform the measurement alone at home and share the data with a physician remotely.

Health monitoring technology has become extremely popular also among consumers. This is not a surprise, as modern wearables, such as smart and sport watches, wristbands, and smart rings, can provide a lot of useful and interesting information from the status of the body, including the level of stress, recovery, and sleep quality. Indeed, such gadgets have made it a common trend to be constantly aware of the level of wellbeing and fitness, and they act as a motivator towards a healthier lifestyle for many. Wearable health monitoring devices have also become so small and comfortable to wear that the user barely notices wearing them (e.g., smart rings), and the data acquisition requires no effort from the user. This is true also for sports and fitness tracking, as a separate chest band is no longer necessary to measure heart rate during exercise due to increasingly accurate wrist-based measurement. At the latest, the COVID-19 pandemic and the need to recognize the infection as early as possible made the benefits from continuous monitoring of vital signs very concrete for the wider public. It is hence not surprising the market grew 8.5% year over year with shipments totalling 116.3 million devices in a recent report by IDC [1].

One of the key features of wearable health monitoring devices is the optical measurement of vital body parameters, including heart rate (HR) and peripheral blood oxygen saturation (SpO2). The measurement of these parameters is based on shining light against the skin by LEDs and measuring the amount of transmitted or reflected light with optical sensors called photodiodes (PD). The accuracy of the measurement is largely affected by the strength of the PD signal. An obvious solution to produce a stronger signal is to increase the power of the LEDs, however, this comes naturally with the cost of battery life – an unwanted effect for consumers who are unwilling to charge their devices too frequently. Another option is to collect light from a larger area. This, however, means that the device would need to be larger, which reduces the amount of freedom the designers have for the location of the diodes and is against the trend of making the devices ever smaller. A third, more effective method for improving the measurement accuracy is to select a PD that has as high sensitivity as possible, which means that it produces a strong signal compared to noise with a given LED power.

It is important to note that not all end user applications aim for maximized accuracy. A trade-off needs to be always made between measurement accuracy, power consumption, and the size of the PD, and different types of wearable health monitoring applications may have different weighting for which parameter to optimize for. For instance, accuracy is likely the most essential parameter for medical wearables, whereas power consumption and battery life are important for smart watches. The area that the PD takes may be a limiting factor for smaller devices, such as smart rings. Nonetheless, a PD with the highest performance can allow an optimum trade-off between these parameters regardless of which is the most desired one.



PHOTOPLETHYSMOGRAPHY (PPG) IN SHORT

The measurement of HR and SpO2 in wearable devices is typically based on a technique called photoplethysmography (PPG) [2]. It is a method to optically measure changes in blood volume in peripheral circulation. In this technique, the PPG module is held firmly against the wearer's skin, which is illuminated by LEDs. A portion of the light is absorbed by the blood, tissue and bones, while some light is transmitted through the body part and some gets reflected. The amount of absorbed light is characterized by measuring the transmitted or reflected light with a PD (Fig. 1a) which produces an electrical signal that is proportional to the light intensity. The former approach (measurement of transmitted light) is used, e.g., in pulse oximeters that measure SpO2 from the patient's fingertip or earlobe, while consumer products, such as smartwatches and rings, more often rely on the measurement of reflected light, since they are typically held on thicker parts of the body which the light cannot penetrate through.

The amount of blood in the arteriae varies periodically with a frequency defined by the rate at which the heart beats. At those moments of time when there is more blood in the artery, which can also be felt as a pulse on the wrist or neck, a larger portion of the light gets absorbed and the intensity of the transmitted/reflected light measured by the PD is smaller (Fig. 1b). The time between two pulses in the light signal denotes one cardiac cycle, and monitoring the number of light intensity peaks as a function of time gives the HR in beats per minute (bpm). In practice, the process is not that straightforward, but advanced signal processing algorithms are able to determine the HR from the periodic variations in the PD signal.

Even though the measurement can detect changes in blood volume in the arteriae, it cannot quantify the amount of blood, since the quantitative light intensity measured by the PD depends on several unknown factors in addition to absorption by the arterial blood. These include absorption by the tissues, bones, and venous blood, and how well the measurement unit is held against the skin.

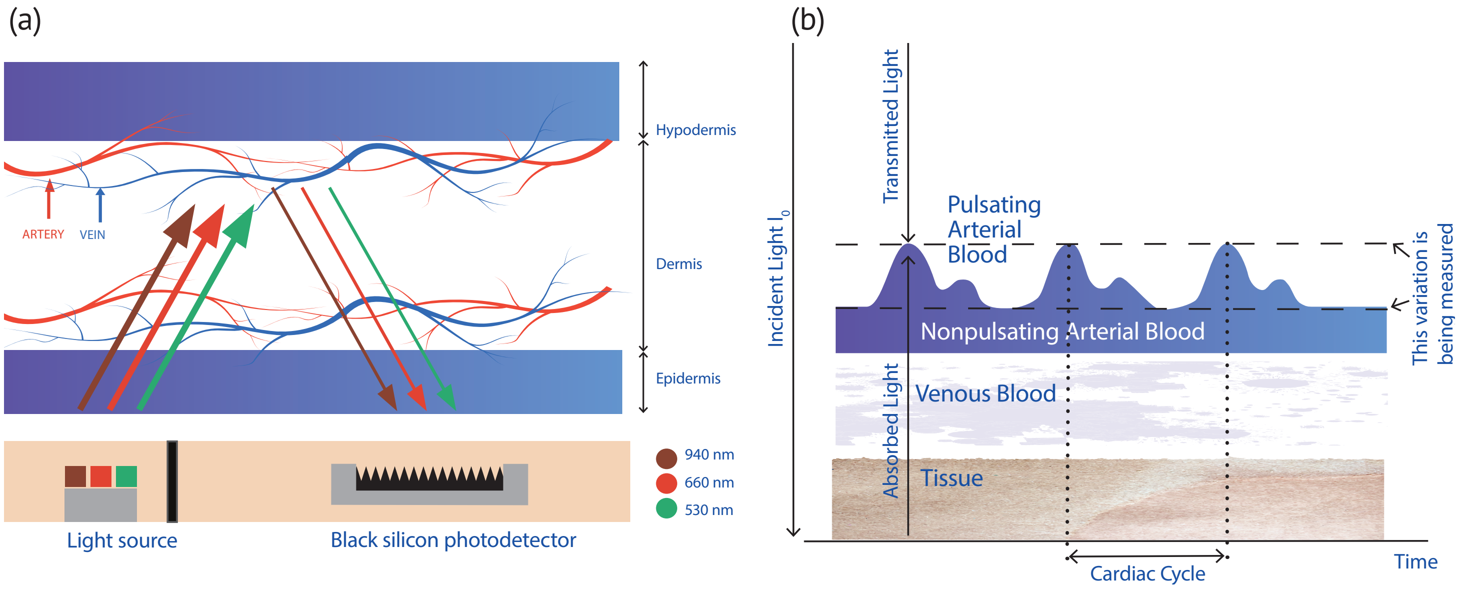


Figure 1. (a) PPG is based on illuminating the skin with LEDs and measuring the reflected or transmitted light with a PD.

(b) Portion of the incident light is absorbed by tissues, venous blood, and arterial blood, and the rest is transmitted through or reflected from the body. The amount of absorbed light varies periodically, since the arterial blood volume changes depending on the phase of the cardiac cycle. HR can be determined by measuring this variation.

Light absorption by blood depends on the wavelength of the light (Fig. 2). Green light is efficiently absorbed by human blood and is therefore typically used for the measurement of heart rate. The absorption depends also on whether the hemoglobin (Hb) molecules in the blood have bonded with oxygen or not. This effect is strongest with red and near infrared (NIR) light, which is why these wavelengths are typically used in PPG to measure SpO2. In this measurement, absorbance of light at two different wavelengths, typically around 660 and 940 nm wavelengths, is measured with a PD.

As seen in Fig. 2, the higher the concentration of oxygenated Hb molecules, the lower the absorbance of red light and the higher the absorbance of NIR light. By comparing the signal level at these two wavelengths, data algorithms can calculate the relative concentrations of hemoglobin and its oxygenated molecule, which yields the blood oxygen saturation level.

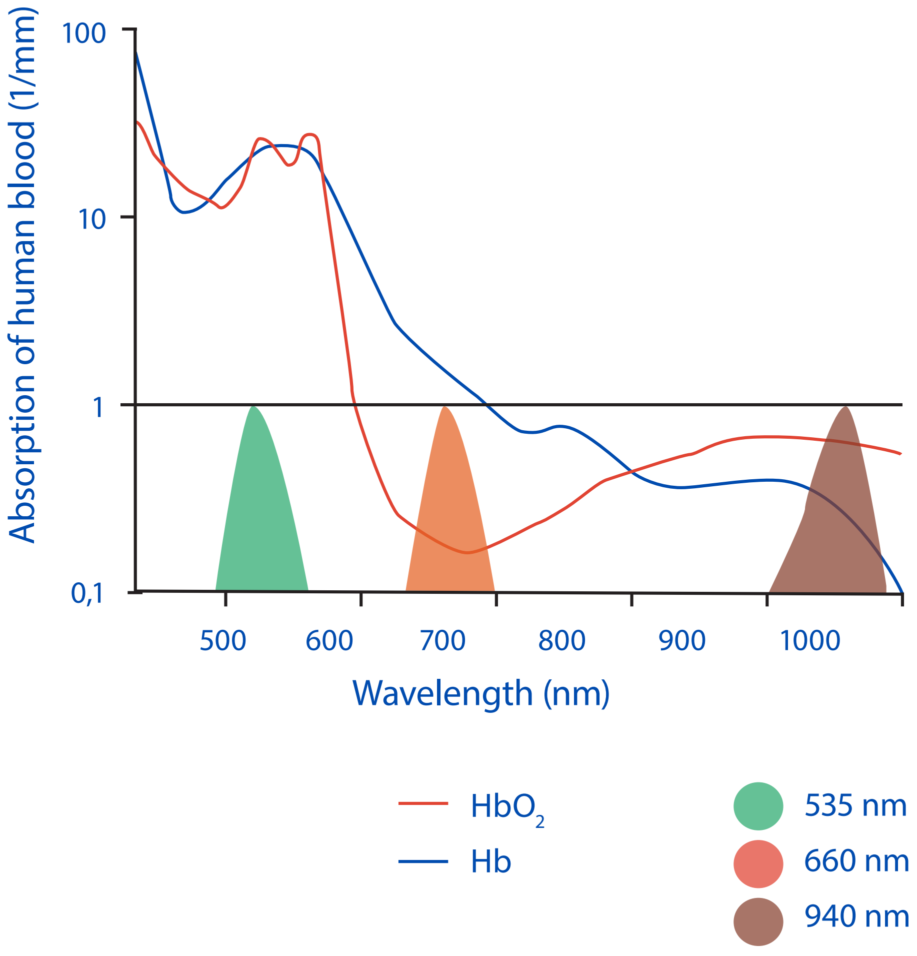


Figure 2. Absorption of light depends on wavelength and whether the hemoglobin molecule is oxygenated (HbO2) or not (Hb). Green light is absorbed efficiently by human blood and is therefore commonly used for HR measurement. Red and NIR are used for SpO2 measurement, since their absorption has different dependence on the hemoglobin oxygenation level.

Another factor affecting the choice of the LED color is the absorption depth of the light. In general, short wavelengths are absorbed closer to the skin surface, whereas longer wavelengths penetrate deeper into the tissue. Green light with rather short wavelength is mostly reflected from the surface tissues, where the amount of blood in the small arteriae varies less with the movement of the user's hand compared to the larger arteriae deeper in the tissue. This results in less noise in the signal caused by the movement of the user. Therefore, green light is favored for the HR measurement in conditions where the wearer is moving, such as during an exercise. Optical measurements relying on red light, e.g., the SpO2 measurement, typically require the user to remain rather still during the data acquisition to be accurate.

A third factor to consider in LED selection, especially for wearable devices, is power consumption. The drawback of green LEDs is that they are in general more power hungry than red or NIR LEDs, since photons with smaller wavelength carry more energy and require thus more electricity to be generated. If green and red LEDs are driven with the same power, the red LED will light up brighter, since it produces higher photon density. In fact, when the wearer is at rest, some devices use red or NIR light also for heart rate measurement to save battery.

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ELFYS BLACK SILICON INDUCED JUNCTION TECHNOLOGY

One of the key components in the PPG module is the PD that measures the light transmitted through or reflected from the body. The PD performance is heavily affected by the efficiency of light absorption. A common method for reducing optical losses is to reduce light reflection from the PD surface by applying an anti-reflection (AR) coating on it. While this technique works well for a single narrow wavelength region, the AR coating may even increase the optical losses on other wavelengths which it has not been designed for.

Instead of an AR coating, ElFys PDs have tiny nanostructures on the front surface (Fig. 3), i.e., black silicon (Si), where light rays get lost. In more scientific terms, the black silicon nanostructures form a graded refractive index layer, and consequently, the incident light does not see an interface between air and silicon and does not get reflected. As a result, reflection from the black silicon surface is virtually zero for a wide wavelength range from ultraviolet (UV) to visible (VIS) and NIR, and all light is absorbed by the silicon material. The black Si also scatters light efficiently, increasing the optical path length, which reduces the transmission of long-wavelength light that travels longer distance in Si before it gets absorbed. Optical losses of ElFys PDs are hence negligible.

100 % absorbance means that every single incident photon generates one charge carrier pair: one electron and one hole. However, high absorbance alone is not enough, but the generated charge carriers need also to be collected efficiently to have high output signal. Charge carrier collection is typically realized in PDs by doping a thin layer of silicon at the PD front surface with dopants of opposite polarity from the Si bulk to form a p-n junction. However, the highly doped layer causes excessive charge carrier recombination, which limits the PD performance especially for short wavelength light that is absorbed within the doped layer.

To avoid these issues, ElFys PDs utilize patented induced junction technology. The black Si nanostructures are coated with a charged thin film, which creates a strong electric field near the PD front surface [3]. The electric field inverts the polarity of the silicon material near the surface (Fig. 3) and creates the p-n junction that is responsible for collecting the electrons and holes. Since no external dopants are needed, the electrical losses are efficiently minimized, also for short-wavelength light.

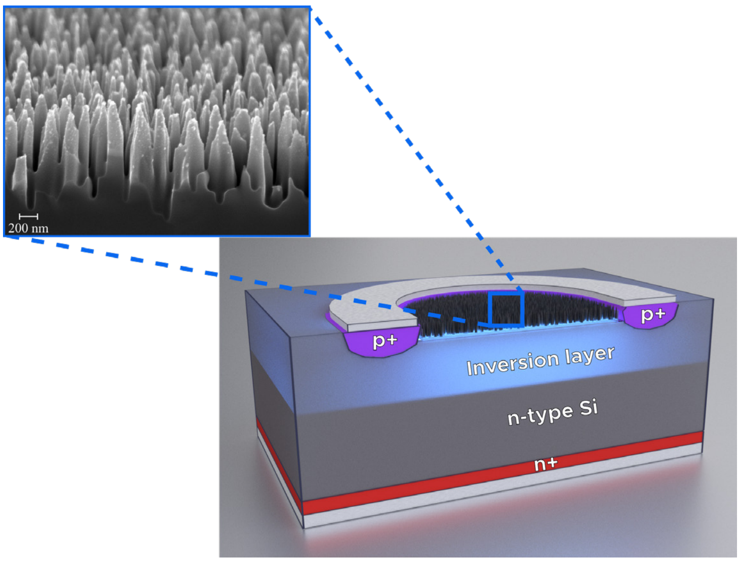

Figure 3. ElFys PDs are based on the patented Black Silicon Induced Junction technology. They have a nanostructured black Si front surface to eliminate optical losses.
Charge carrier collection is realized via induced junction technology: a highly-charged thin film coating on the black Si surface inverts the polarity of the PD front surface and enables a "recombination-free" p-n junction.
Note that the figure presents a generalized PD structure and not any specific ElFys product.

The performance of a PD to measure light can be presented as a parameter called external quantum efficiency (EQE). It describes how many charge carriers are collected from the device per incident photon. An ideal PD would have an EQE of 100 %, which means that if 100 photons hit the PD front surface, 100 charge carriers are collected in the external circuit and no carriers are lost due to optical or electrical losses.

The EQE of ElFys Black Silicon Induced Junction PDs is presented in Figure 4. ElFys PDs have nearly 100 % EQE for the whole UV-VIS-NIR wavelength range from 200 to 1000 nm [4, 5], meaning that they can literally Capture every single ray of light. The EQE is over 99 % for most of the wavelengths with a minimum of as high as >96 % at around 350 nm. The near-ideal EQE demonstrates that the black Si nanostructures indeed eliminate all optical losses and also the electrical losses are negligible thanks to the induced junction and other advanced techniques to efficiently minimize charge carrier recombination in the Si material and its surfaces. The EQE is even higher than 100 % in the deeper UV, which is possible, since the photons with that short wavelength have so high energy that they can generate more than one charge carrier pair per photon [6, 7]. This part of the spectrum is absorbed very close to the front surface inside the black Si nanostructures, and >100 % EQE shows that there are very minimal recombination losses due to defects within the nanostructures or at their surfaces.

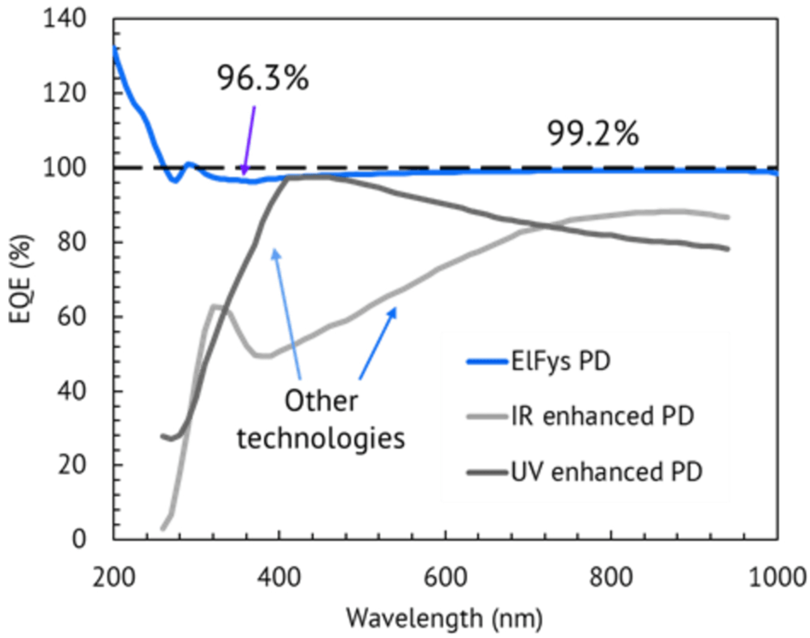

Figure 4. The patented Black Silicon Induced Junction technology enables near 100 % external quantum efficiency (EQE) over a wide range of wavelengths in UV-VIS-NIR, meaning that ElFys PDs can "Capture every ray of light". The improvement compared to other technologies is clear. Notably, the conventional PDs can be optimized only for a narrow wavelength region.

Figure 4 also compares the performance of ElFys products to competing devices, which have been optimized for UV and NIR spectral ranges according to their manufacturers. The EQE spectra of the competing devices show that while relatively high performance can be achieved on a certain narrow wavelength range, the EQE quickly drops when moving away from the region the device is optimized for. For maximized performance in applications where multiple wavelengths are of interest, a separate PD would be needed for each part of the spectrum. A single ElFys PD can cover the whole UV-VIS-NIR range with high performance. The figure also reveals that it is challenging to achieve high UV performance with PDs relying on the traditional doped p-n junction technology. The sensitivity of ElFys induced junction-based PDs is several times higher than even the UV enhanced PD from the competitor.

HIGH-PERFORMANCE PHOTODIODES FOR WEARABLE HEALTH MONITORING

Selection of the PD has a major impact on the accuracy of the PPG measurement. Since the device is responsible for catching the transmitted or reflected light signal, its performance determines the quality of the raw measurement data regardless of the used software algorithm.

As presented in the previous section, ElFys provides high-performance PDs based on the patented Black Silicon Induced Junction technology. The ElFys SM product series is specifically designed for wearable health monitoring applications, where high sensitivity is required. These PDs are packaged in a surface-mount type of package with the PD attached on a printed circuit board (PCB) and molded in optical epoxy for surface protection. Standard sizes of 3.22 mm2 and 4.46 mm2 are available off the shelf for easy drop-in replacement, but the products can also be flexibly customized to fulfill customer-specific requirements.

One of the most important parameters on PD performance for PPG applications is photoresponse, which tells how large output current the PD produces per Watts of incident light. Higher value means that smaller amount of light is enough to produce equally strong signal, or analogously, the electrical signal is stronger for the same amount of light. Figure 5 presents a typical response spectrum of packaged ElFys SM series products compared with another state-of-the-art PD often used for PPG. ElFys patented Black Silicon Induced Junction technology provides ~50 % improvement for the sensitivity at green, and the photoresponse is as high as 0.40 A/W at 540 nm wavelength. The response is nearly ideal also at red, where ElFys technology improves the performance by >15 % to 0.47 A/W at 630 nm.

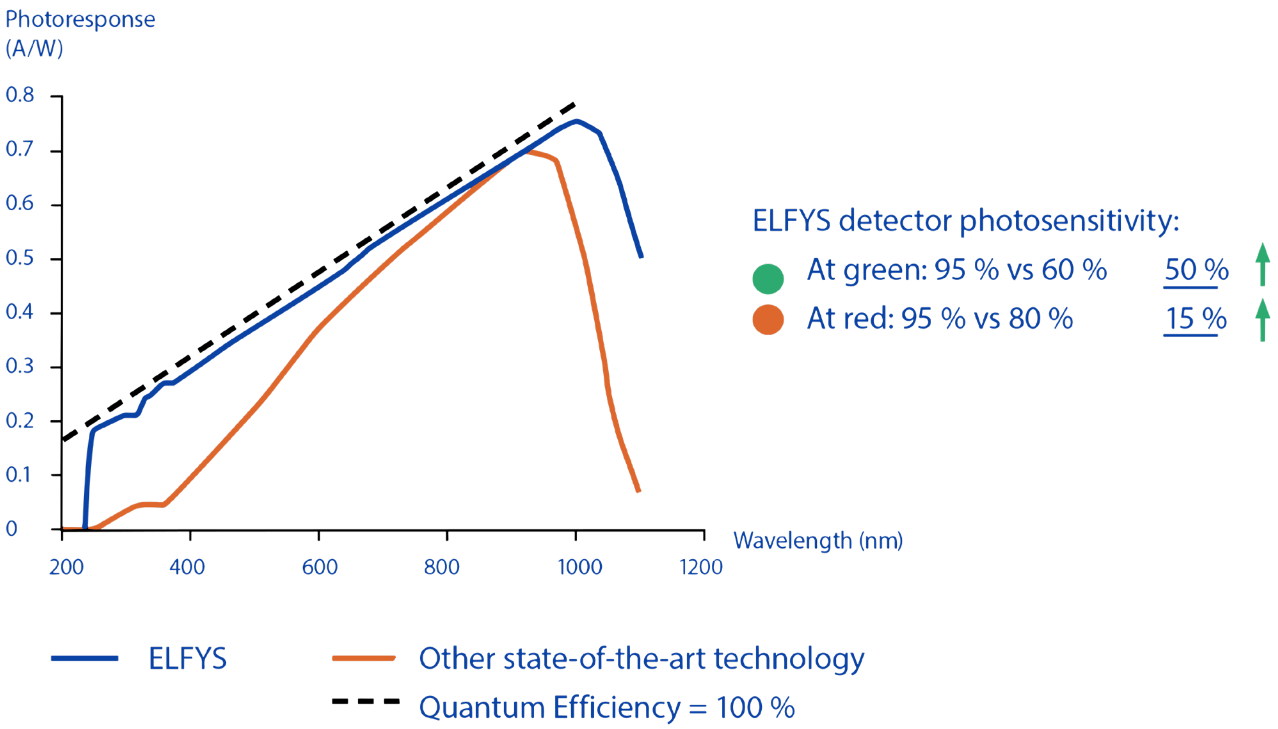

Figure 5. Photoresponse of ElFys Black Silicon Induced Junction PDs compared to other state-of-the-art PD products often used in PPG. ElFys technology provides ~50 % sensitivity improvement for green light and produces >15 % stronger signal for red light.

As the noise levels of the products compared in Fig. 5 are similar, difference in response directly tells the difference in signal to noise ratio. ElFys SM components hence produce up to ~50 % higher signal with a given light intensity compared to other state-of-the-art products, meaning a great improvement in the PPG measurement accuracy. The higher sensitivity also means that smaller light intensity can be measured more accurately, and a weaker light signal produces equally strong electrical output from the PD. The LEDs of the PPG module can hence be driven with a smaller current, which reduces the power consumption of the measurement and provides a possibility to improve the device battery life. A third benefit of the higher photoresponse is that the same signal level can be obtained from a PD with a smaller footprint. This gives wearable device manufacturers more freedom in optimizing their design and enables making the devices ever smaller.

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END-USER BENEFITS OF IMPROVED PHOTODIODE PERFORMANCE

Improved photodiode performance provides several concrete benefits for the users of wearable health monitoring devices. The higher sensitivity of light measurement may enable detecting new body parameters which has not been possible before due to limited accuracy. This could open completely new use cases for optical measurement techniques and result in new applications for wearable devices. In medical use, higher measurement accuracy can lead to more accurate monitoring of vital signs and improve diagnosis, which can potentially even save lives. On the other hand, if the patients can monitor and examine themselves at home and require only remote consultation by a nurse or doctor, the amount for resources needed in health care is reduced, which is crucial in modern societies where population is getting older at the same time when there is a lack of educated personnel. Also consumer wearables support the same goal, if they make people more interested in their wellbeing and motivate them to follow a healthier lifestyle, reducing the need for healthcare.

Constant monitoring of vital signs with ever more sensitive sensors may also help to detect diseases earlier. A wearable may reveal, e.g., arrhythmia or sleep apnea before the wearer has any clear symptoms, and proper medical treatment can be started well in time before the disease has become too severe. The benefits of constant monitoring became very concrete during the COVID-19 pandemic, as wearable users knew to stay at home after being infected even days before the first symptoms appeared by following changes in their HR and body temperature and did not spread the disease further.

In sports, optical measurements have enabled HR-based training without the need for a separate uncomfortable chest strap. However, the accuracy of the measurement has been limited for some types of sports, where the heart rate needs to be known with very high accuracy. Improved sensitivity will alleviate these issues. In some other sports, such as ultrarunning or hiking, higher PD performance can be utilized in the form of reduced energy consumption, as battery life is of utmost importance when the sports activity can last even several days.

Ability to use smaller PDs without sacrificing the measurement accuracy enables design of ever smaller wearables. Already today wearable health monitoring devices are not limited to smart watches, but there are also smaller gadgets such as rings and earbuds available on the market. With improved PD performance, the designers have more freedom on the PPG module dimensions and even finer devices may be designed, including different forms of jewelry.

CONCLUSION

In this paper, we have explored the significance of high-performance photodiodes for wearable health monitoring. As the use of wearable healthcare technology proliferates in clinical and everyday contexts, the accuracy of vital sign monitoring, such as heart rate and blood oxygen levels, is crucial. ElFys Black Silicon Induced Junction technology revolutionizes PD performance by eliminating optical and electrical losses, resulting in near-ideal EQE and stronger signal than obtained with any other PD product. This advancement translates into tangible benefits for end users, from more precise medical diagnoses to early disease detection. It also enhances sports training, reduces power consumption, and enables smaller, more discreet wearables. As we embrace a future where health and wellness are paramount, these innovations promise a new era of wearable health monitoring, improving lives and healthcare efficiency.

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ABOUT ELFYS,INC.

ElFys, Inc. was founded in 2017 and is located in Espoo, Finland. The company is based on long-term research work on photodetector technologies at Aalto University. Our core team consists of former senior researchers, engineering leaders and business professionals. The company utilizes the state-of-the-art processing facilities at Micronova Nanofabrication Center in Espoo, Finland: 2600 square meters of CMOS compatible facilities suitable for both R&D and semi-mass production. For high-volume mass production, ElFys has partnered with an external, European foundry.

ElFys provides light sensors with better sensitivity than anything seen before, literally catching every ray of light. The technology greatly improves any light sensing application ranging from health monitoring to analytical instrumentation and security X-ray imaging. The superior performance of ElFys photodetectors is based on an inventive combination of modern MEMS nanotechnology and atomic layer deposition. The core technologies are patented and in the possession of the company.

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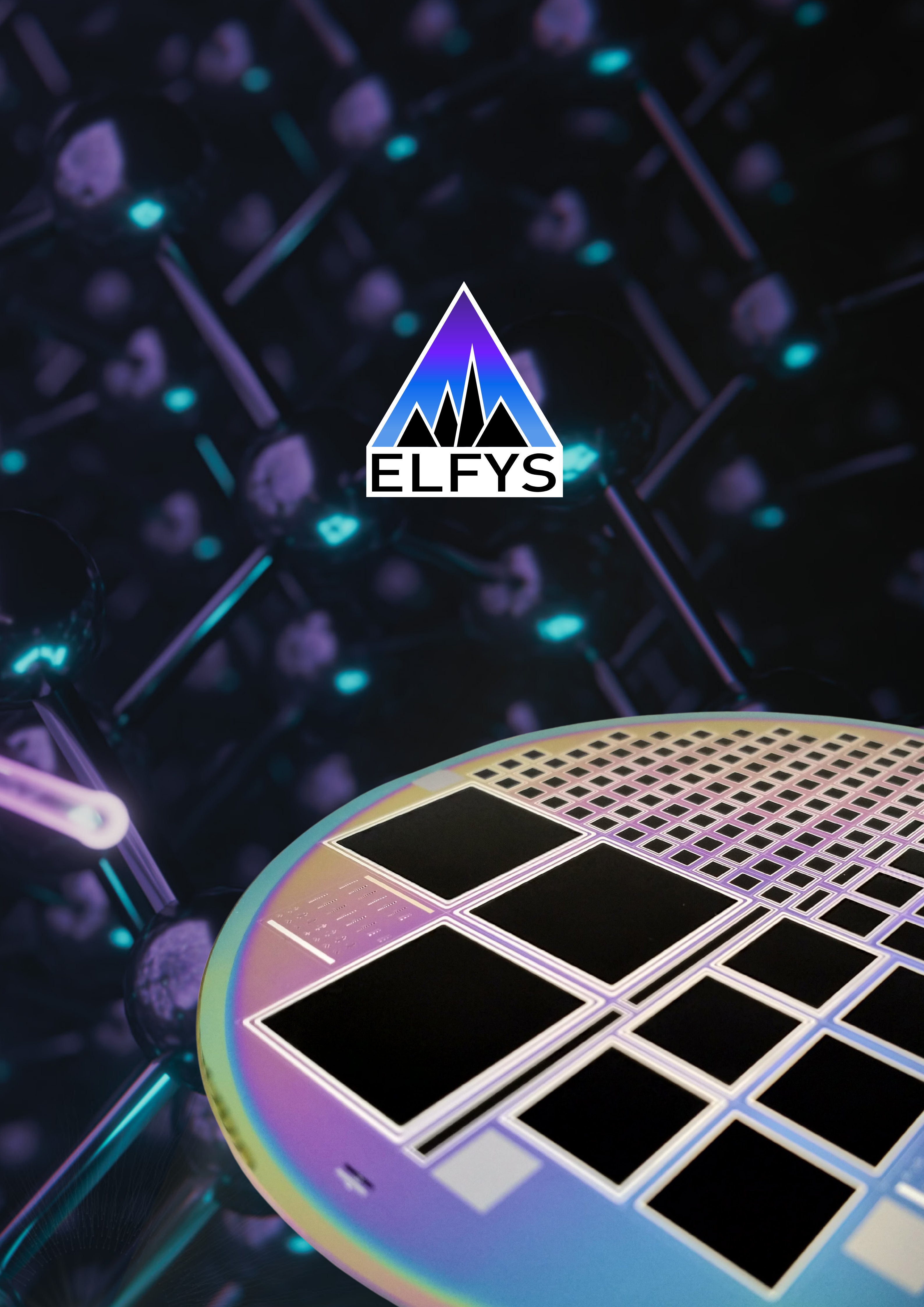
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