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Improvement of Infrared Detectors for Tissue Oximetry using Black Silicon Nanostructures

S. D. Petersen[a]*, R. S. Davidsen[a], L. R. Alcalá[a], M. S. Schmidt[a], A. Boisen[a], O. Hansen[a], E.V. Thomsen[a]

[a]*DTU Nanotech, Technical University of Denmark, Kongens Lyngby, DK-2800, Denmark*

Abstract

We present a nanostructured surface, made of dry etched black silicon, which lowers the reflectance for light incident at all angles. This surface is fabricated on infrared detectors used for tissue oximetry, where the detection of weak diffuse light signals is important. Monte Carlo simulations performed on a model of a neonatal head shows that approximately 60% of the injected light will be diffuse reflected. However, the change in diffuse reflected light due to the change in cerebral oxygenation is very low and the light will be completely isotropic scattered. The reflectance of the black silicon surface was measured for different angels of incident and was fund to be below 10% for angles of incident up to 70°. The quantum efficiency of detectors with the black silicon nanostructures was measured and compared to detectors with a simple anti-reflection coating. The result was an improvement in quantum efficiency for both normal incident light and light incident at 38°.

Peer-review under responsibility of the scientific committee of Eurosensors 2014.

Keywords: Tissue oximetry; infrared detectors; black silicon; quantum efficiency; diffuse reflected light

1. Introduction

Near infrared tissue oximetry, as a medical diagnostic method, is next in line to continue in the successful footsteps of pulse oximetry, which today is widely used at hospitals. Tissue oximetry is of special interest within

* Corresponding author. Tel.: +45-45255692; fax: +45-45887762.
E-mail address: sdpet@nanotech.dtu.dk

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neonatology where it is used to non-invasively monitor the oxygenation of brain tissue on prematurely born infants [1]. The most widely used measurement method is spatially resolved spectroscopy (SRS) where light of different wavelengths is injected into the tissue and the diffuse reflected light is measured as a function of distance to the light source, generally done using distances of several centimeters, see Fig. 1a. We have previously presented a device for SRS measurements on neonates, consisting of nine individual detectors, made from silicon polyimide and PDMS and optimized for detection of light with a wavelength of 700-1000 nm, which can be seen in Fig. 1b [2].

Although a majority of the light is diffuse reflected from most tissue types the changes in signal due to changes in cerebral oxygenation are typically small. In order to maximize the detected signal the reflectance from the surface of the detectors should be as low as possible. A typical solution is to apply anti-reflection (AR) coatings to the detector surface, but such coatings are very dependent on the incident angle of light and the diffuse reflected light will be incident on the detectors at all angles (0-90°). We present a solution to this problem by using black silicon nanostructures, which are dry etched into the silicon surface of the detectors. Black silicon has already proven to be a very effective anti-reflection surface for solar cells because it offers low reflectance for a wide range of wavelengths as well as for a wide range of incident angles [3].

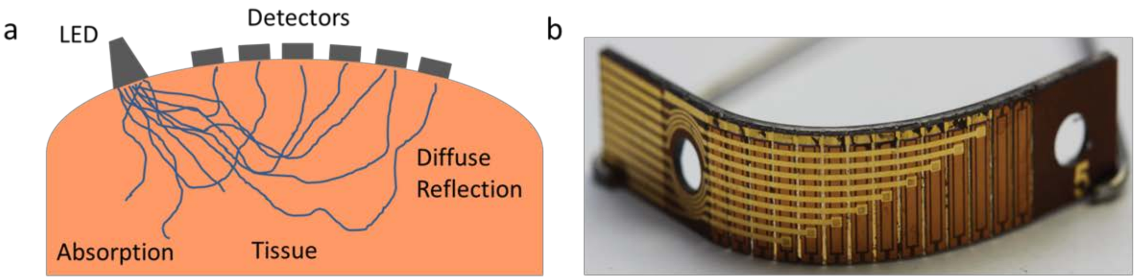

Fig. 1. (a) The principle behind spatially resolved spectroscopy. (b) A flexible array of infrared detectors used for tissue oximetry.

2. Results and discussion

2.1. Monte Carlo simulations

In order to investigate how the diffuse reflected light will behave as a function of cerebral oxygenation for a neonate we have used Monte Carlo simulation on a model of a neonatal head [4]. The model consists of four different layers corresponding to the skin, the skull, the cerebrospinal fluid and the cerebral tissue into which a pencil beam of light is injected. When the cerebral oxygenation changes it will lead to a change in the ratio between oxygenated hemoglobin and deoxygenated hemoglobin. This will in turn change the absorption coefficient of the cerebral tissue. Using data of the absorption coefficient for the two different types of hemoglobin the change in diffuse reflected light can be simulated as function of the cerebral oxygenation (StO2) for different wavelengths [5]. The results can be seen in Fig. 2a, which shows the diffuse reflected light as function of cerebral oxygenation for three different wavelengths. It can be seen that approximately 60% of the injected light will be diffuse reflected. However, the change in diffuse reflected light due to the change in cerebral oxygenation is very small, which indicates that the infrared detectors need to be of very high quality. Furthermore, the distance which the light has to travel before being completely isotropic scattered can be described as being greater than the inverse of the reduced scattering coefficient, which for the tissues in a neonatal head will be approximately 20 cm^{-1}. This means that the light will be isotropic scattered after travelling >0.5 mm into the tissue. The diffuse reflected light will therefore be both very weakly changing as function of cerebral oxygenation and arrive at the detectors from all angles between 0-90°.

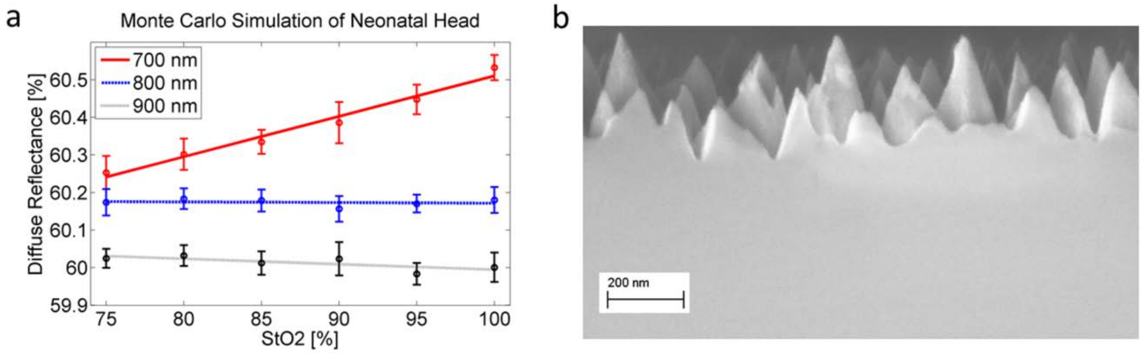

Fig. 2. (a) Results from Monte Carlo simulations. (b) SEM image of the black silicon nanostructures.

2.2. Device fabrication

The infrared detectors are fabricated on high quality (001) p-type silicon wafers with a resistivity of 10,000 Ω/cm. The detectors are fabricated as back side pn-junction diodes, using boron and phosphorous diffusions, where the junction is located on the opposite side of the light incident surface. This ensures that the electrical interconnects will not obscure for the incident light. A p-type front side field doping is also made by diffusion, in order to ensure that the generated minority carrier electrons will not diffuse towards the front side surface where the recombination velocity will be very high. The back side electrical interconnects are made by aluminum metallization and finally the black silicon nanostructures are etched into the front side using RIE with an SF_6/O_2 plasma. The black silicon nanostructures have a random topology and a height of 100-300 nm, as can be seen from Fig. 2b. Other devices where fabricated with a 50 nm SiO_2 / 50 nm SiN anti-reflection coating instead of the black silicon nanostructured surface. This ensured that the performance of the black silicon surface could be compared to a more standard AR coating.

The dry etching process for making the black silicon nanostructures has the advantage that it is compatible with polymers and metals that are on the silicon wafers when the etching process is performed. This is essential for many medical devices made from a silicon wafer platform, where a wet etch used for fabrication of the black silicon is not possible [6].

2.3. Reflectance and quantum efficiency measurements

The reflectance of the black silicon and the SiO_2/SiN AR coating were measured for light with a wavelength of 700-1000 nm using an integrating sphere and an ellipsometer, respectively. The result can be seen in Fig. 3a. For all the measured angles the black silicon can be seen to have a lower reflectance when compared to the AR coating. The quantum efficiency where measured, as a function of wavelength, for finished devices with both the black silicon nanostructures and the AR coating. The measurements were performed using a monochromator with 10 nm steps and a calibration photodiode with a known responsively and were done for normal incident light and light incident at 38° (the largest possible angle for our setup). The results can be seen in Fig. 3b. The devices with the black silicon nanostructures can be seen to have larger quantum efficiency for almost the entire wavelength span. For the entire spectrum (700-1000 nm) the devices with the black silicon nanostructures have an average quantum efficiency of 83.7% and 79.1% for light incident at 0° and 38° respectively. Whereas the devices with the AR coating have an average quantum efficiency of 74.1% and 61.6% for light incident at 0° and 38° respectively.

The anti-reflection properties of the black silicon nanostructures are seen to outperform the SiO_2/SiN AR coating both in terms of dependence on wavelength and angle. The quantum efficiency is higher for the devices with the black silicon nanostructures in the entire spectrum (700-1000nm). Furthermore, the quantum efficiency is only decreasing with 5.4% for the devices with the black silicon nanostructures when the incident angle is increased to 38°. For the devices with the AR coating the decrease is 16.9%. For many commercial infrared detectors for medical use an IR transparent plastic coating is used, which acts as a cut-off filter for wavelengths below 700 nm. These commercial devices exhibit the same high quantum efficiency as the black silicon devices presented in this paper, but they still suffer from a strong angular dependence for the reflectance. For a typical commercial IR photodiode, coated with such a filter, a quantum efficiency reduction of approximately 25% at a light incident angle of 40° is normal [7].

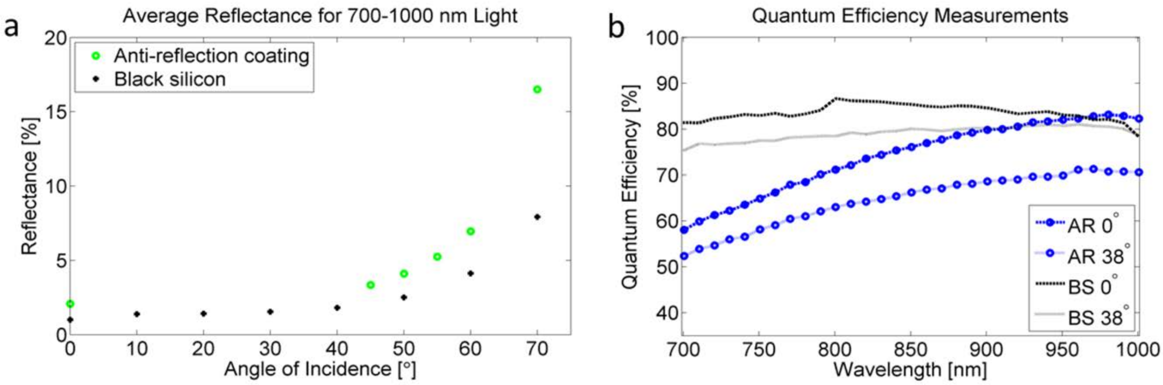

Fig. 3. (a) Reflectance measurements of AR coating and black silicon nanostructures. (b) Quantum efficiency measurements.

3. Conclusion

We have presented a black silicon nanostructured surface, which have been used to improve the anti-reflection capabilities for infrared detectors for tissue oximetry. The importance of the detector improvement has been proven by Monte Carlo simulations that showed how the diffuse reflected light would only be weakly dependent on the cerebral oxygenation and be completely isotropic scattered. The black silicon nanostructures are fabricated using a dry etch RIE process, which is compatible with wafers containing polymers and metals making it useful for various applications. Investigations of the black silicon nanostructured surfaces showed a decrease in reflectance for angles from 0-70° when comparing with a standard AR coating. Furthermore, the anti-reflection effect of the black silicon nanostructures was tested on infrared detectors. This showed higher quantum efficiencies for devices with the black silicon nanostructures at two angles when comparing them to devices with an anti-reflection coating and thus an improvement for the devices ability to detect weak diffuse scattered light.

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