Monolithic integration of a plasmonic sensor with CMOS technology

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ABSTRACT

Monolithic integration of nanophotonic sensors with CMOS detectors can transform the laboratory based nanophotonic sensors into practical devices with a range of applications in everyday life. In this work, by monolithically integrating an array of gold nanodiscs with the CMOS photodiode we have developed a compact and miniaturized nanophotonic sensor system having direct electrical read out. Doing so eliminates the need of expensive and bulky laboratory based optical spectrum analyzers used currently for measurements of nanophotonic sensor chips. The experimental optical sensitivity of the gold nanodiscs is measured to be 275 nm/RIU which translates to an electrical sensitivity of 5.4 V/RIU. This integration of nanophotonic sensors with the CMOS electronics has the potential to revolutionize personalized medical diagnostics similar to the way in which the CMOS technology has revolutionized the electronics industry.

Keywords: Plasmonic sensors, nanophotonics, CMOS, nanophotonics-microelectronic integration

1. INTRODUCTION

There has been a tremendous advancement in developing nanophotonic based sensors due to the many advantages on offer such as label free sensing, high sensitivity and superior detection limit[1,2]. Substantial work has been done to improve the performance parameters of nanophotonic sensors such as sensitivity and detection limit. In addition, significant efforts have been put forward to miniaturize the sensor chips[3]. However, one drawback associated with most nanophotonic sensors is that they require external laboratory based equipment for their measurement such as an optical spectrum analyzer which are not only expensive but also due to their large size they are not practical to use in everyday life. Due to this limitation nanophotonic sensors have failed to achieve wide spread applications in daily life and so far have been restricted to laboratory based demonstrations only. This so called "chip in a lab bottle neck" in the widespread application of nanophotonic sensors can be removed by monolithic integration of nanophotonic sensors with detectors to have a direct electrical readout instead of measuring the resonance wavelength shift of the nanophotonic sensors. For integrating nanophotonic sensors with detectors, the detectors made by Complementary Metal Oxide Semiconductor (CMOS) technology such as photodiodes (PD) are an obvious choice due to a range of benefits on offer such as low cost, high integration density and ease of merging electronics and photonics functionalities. Furthermore, CMOS technology has proven to be the main player in revolutionizing the electronics industry especially in computing and telecommunications. Merging nanophotonics technology with the CMOS technology not only has the potential of transforming laboratory based nanophotonic sensors into practical devices but also paves the way to revolutionize the sensing industry.

There has been only limited efforts on integrating nanophotonic sensors with detectors to develop a compact and miniaturized sensor system including the readout setup. A direct electrical readout was obtained by integrating nanophotonic sensors with a bulk silicon diode but the large size of the diode compromises the compactness of the sensing system[4]. In another work, a nanophotonic sensor was integrated with the CMOS imager but the CMOS imaging chip and the sensor chip were separate which increases the distance between the nanophotonic structures and detectors[5].

Furthermore, holders are required to keep the chips together and aligned which precludes the advantage of compactness that monolithic integration can offer.

In this work, we have monolithically integrated resonant nanophotonic sensors with the CMOS photodiodes (PD) and have developed a compact nanophotonic sensor system having direct electrical readout hence eliminating the need of an optical spectrum analyzer for measuring the sensor chip. This approach of monolithic integration of nanophotonic sensors with CMOS technology has the potential to transform laboratory based nanophotonic sensors into practical devices with a range of applications in everyday life especially in point of care diagnostics.

2. DESIGN OF PLASMONIC SENSOR

One of the most important phenomena on which nanophotonic sensors operate is called refractive index sensing where a change in the refractive index of the environment surrounding the nanophotonic structures causes a shift in the resonance wavelength of the resonant nanophotonic structures[6]. The performance of resonant nanophotonic sensors is mostly gauged by the degree of wavelength shift per change in refractive index which is called sensitivity and expressed in units of nm/RIU (refractive index units)[7]. However, once nanophotonic structures are integrated with PD, the parameter that matters is the change in the optical intensity due to wavelength shift impinging on the PD which makes the resonance linewidth and resonance depth also important. The change in optical intensity due to wavelength shift can be enhanced by high sensitivity, narrow resonance linewidth and large resonance depth. While designing the nanophotonic sensors for integration with CMOS detectors the choice of material and design should be selected which simultaneously gives high sensitivity, narrow linewidth and large resonance depth. Metallic nanophotonic sensors are reported to have high sensitivity due to exploiting plasmonic responses such as surface plasmon resonance or extraordinary optical transmission [8-10]. But the drawback in using plasmonic sensors is a broad resonance linewidth due to the large optical losses associated with metals. On the other hand resonant nanophotonic sensors made of dielectric structures such as silicon nitride cavities or gratings can achieve very narrow resonance linewidths but their sensitivity is lower compared to the plasmonic sensors[11]. Hence, there is a tradeoff in the choice of material for nanophotonic sensors designed for integration with CMOS detectors which also depends on the applications. For example, when measurement of large changes in refractive index is required, broad linewidth plasmonic sensors are a better choice whereas the very narrow resonance linewidth of dielectric structures will saturate the signal. On the other hand, for measuring very small changes in refractive index, high Q-factor (narrow linewidth) resonant dielectric structures are better choice. In the present work, we selected plasmonic nanostructures for integration with CMOS detectors due to their higher sensitivity and easy fabrication protocol for monolithic integration with the CMOS detector chip. By using a Finite Element Method (FEM) based commercial software, Comsol Multiphysics, we designed an array of gold nanodiscs having the resonance wavelength below the bandgap of silicon (wavelength smaller than 1100 nm). The periodicity of the array and diameter of the gold nanodiscs were optimized to keep the resonance linewidth as narrow as possible while maintaining the resonance depth. The gold nanodiscs array having periodicity of 450 nm, diameter 200 nm, and thickness 60 nm has a resonance wavelength at 750 nm with 80 nm linewidth and 70 % resonance depth, as shown in the transmission spectrum in Figure 1.

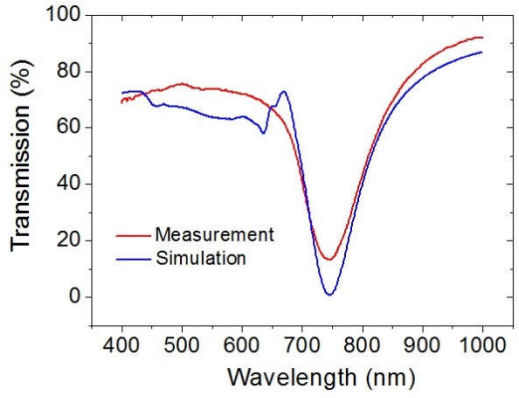

Figure 1 Simulated (blue curve) and experimental (red curve) transmission spectra of gold nanodiscs array with glass substrate having the following physical parameters; periodicity 450 nm, diameter 400 nm, thickness 60 nm.

Our CMOS PD has the highest responsivity at 600 nm and as such it is better to design nanophotonic structures that match the highest responsivity range of the PD. However it was not possible to design a gold nanodisc array that has a resonance wavelength lower than 750 nm due to the lower plasma frequency of gold. The resonance wavelength can be lowered by using other metals instead of gold such as aluminium which are reported to cover the whole visible spectrum. However, aluminum oxidizes very quickly which degrades the sensor performance. The problem of oxidation can be mitigated by depositing a thin passivation layer on top of aluminum nanostructures but it will reduce the sensitivity because the highest intensity of the electrical field lies at the interface of the metal and dielectric and decays very quickly with the distance from the interface, as shown in Figure 2.

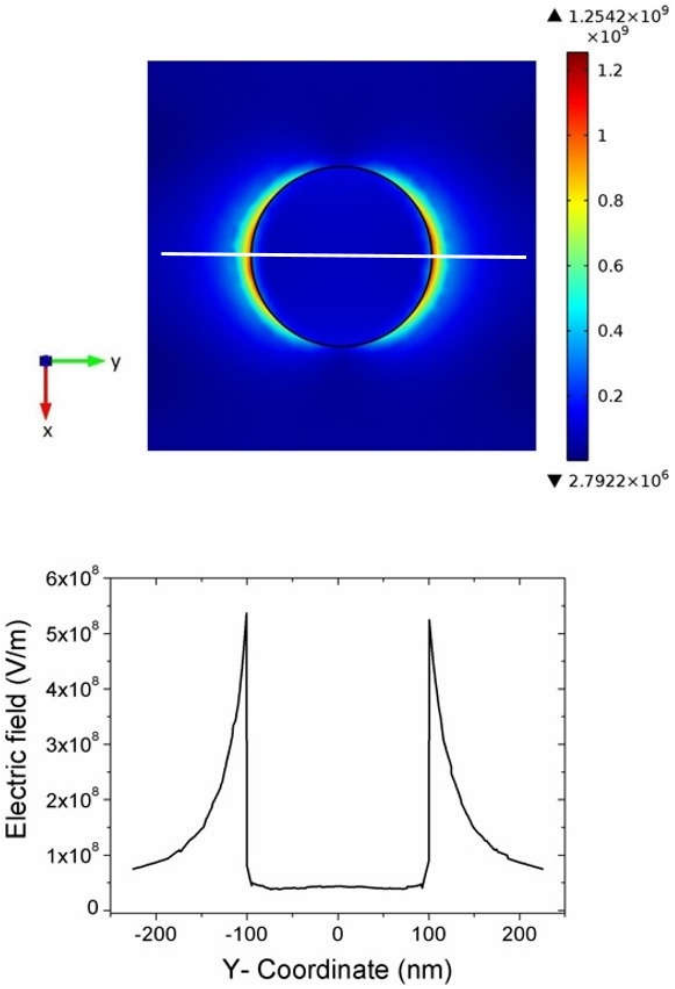

Figure 2: Electric field distribution at the resonance wavelength of the gold nanodiscs.

Thus, to keep the sensitivity high and avoid the oxidation problem we used nanodiscs made of gold which has a resonance wavelength higher than the highest responsivity range of the CMOS detector but is still within the range where the responsivity is reasonably high.

3. EXPERIMENTAL DETAILS

3.1 Fabrication of gold nanodiscs on a glass substrate

Test samples of gold nanodiscs array were fabricated on a 500 µm thick borosilicate glass substrate to measure their transmission and sensitivity responses. The samples were fabricated by e-beam lithography followed by the lift off process. A 200 nm thick bi-layer of PMMA was spin coated on the glass substrate and gold nanodisc structures were defined in the resist by a 100 KV e-beam. After developing the exposed resist in 2:1 IPA: MIBK solution, the sample was cleaned by oxygen plasma to clear any leftover thin layer of resist from the developed area. A 60 nm layer of gold was then evaporated using an e-beam metal evaporator. Prior to gold deposition, a 3 nm layer of titanium was deposited to ensure better adhesion of the gold layer making the total thickness of the metal layer equal to 63 nm. The effect of thin titanium layer on the optical response of gold is negligible as long as the thickness of the gold layer is kept constant[12]. The residual resist was then removed during the lift-off process by using acetone. The dimensions and quality of the fabricated structures were analyzed using a scanning electron microscope (SEM). The SEM images of the fabricated sample are shown in Figure 3.

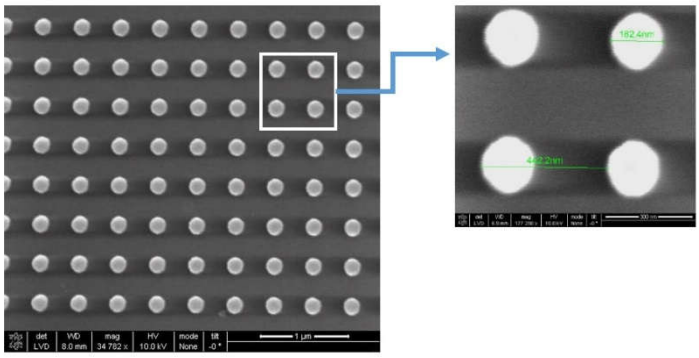

Figure 3: Scanning electron microscope (SEM) images of gold nanodiscs fabricated on top of a glass substrate.

3.2 Characterization

The transmission response of the gold nanodisc array samples was measured by using a commercial microspectrometer. Unpolarized light from a halogen lamp was incident on the samples and collected by a 4x microscope objective having numerical aperture of 0.1 by using a Leica 2700M microscope. The transmitted light collected by the objective was fed to the spectrometer via an optical fiber which gives the transmission spectrum of the samples. The resolution of the setup used is limited to 1 nm.

The experimentally measured transmission response of the gold nanodiscs array fabricated on a glass substrate is shown in Figure 1 (red curve), which matches well with the simulated transmission response (blue curve) in terms of resonance wavelength and linewidth. A small peak at 675 nm is observed in the simulated transmission spectrum which corresponds to the Rayleigh – Wood anomaly which can be calculated analytically by following the procedure given in ref [13].

4. SENSITIVITY ANALYSIS OF GOLD NANODISC ARRAY

The performance of the gold nanodisc array as a refractive index sensor was analyzed by applying different concentrations of glycerol on top of the nanodiscs. Increasing the concentration of glycerol in DI water increases the refractive index [14] which causes a red shift of the resonance wavelength as shown in Figure 4. A 10 % change in the glycerol concentration (refractive index change, $\Delta n \approx 0.011$) induces a 3 nm wavelength shift. Hence, the sensitivity of the gold nanodiscs array is measured to be 275 nm/RIU.

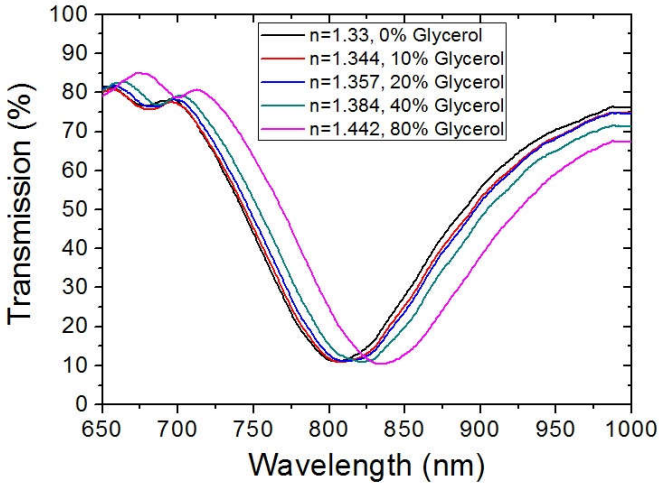

Figure 4: Experimentally measured red shift of the resonance wavelength of the gold nanodiscs array on applying different concentrations of glycerol in DI water.

5. INTEGRATION OF PLASMONIC SENSOR WITH CMOS PD

The CMOS PD chip was manufactured in the commercial foundry Austriamicrosystems, Austria. A 0.35 µm, four metal high voltage CMOS process was used. The dimensions of the PD is only 6x8 µm. Figure 5a shows a microscopic image (x100) of two PDs fabricated on the same CMOS chip. On top of one PD (encircled in black, left in figure 5a) the gold nanodiscs array is fabricated while the second one (encircled in white, right in Figure 5a) is used as a reference. The cross section of the PD CMOS chip is given in Figure 5b.

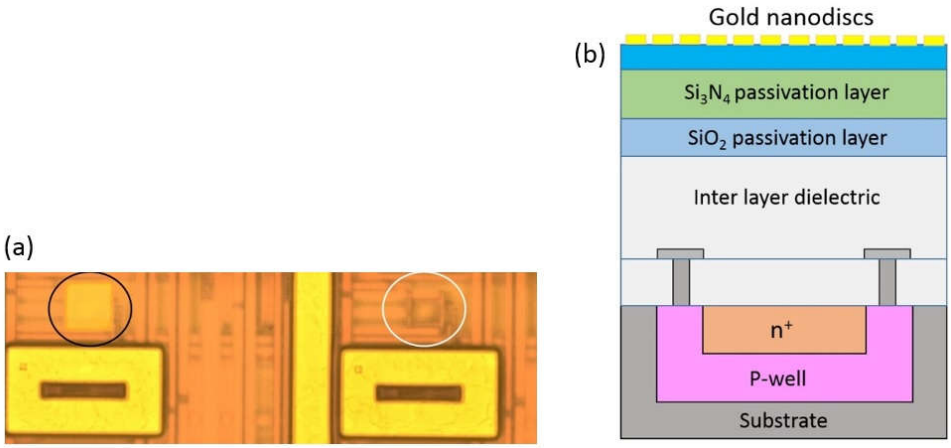

Figure 5: (a) Microscope image (x100) of CMOS PDs with integrated gold nanodiscs (left, encircled in black) and without nanodiscs (right, encircled in white). (b) Cross section schematic of the CMOS chip with gold nanodiscs on top.

For monolithic integration of gold nanodiscs with the CMOS PD chip first a 500 nm layer of silica was deposited on top. The main purpose of this deposited silica layer was to ensure that the resonance wavelength of the gold nanodiscs do not shift to higher wavelengths due to larger refractive index of the passivation layer of the CMOS chip which is often composed of silicon oxy nitride which has higher refractive index than silica in the operating wavelength range. After depositing the 500 nm silica layer, the gold nanodiscs array was fabricated on top of it by using the same fabrication method as described in section 3.1. The alignment of the nanodiscs on top of the PD was carried out by using alignment markers defined on the CMOS chip. As a last step, the deposited silica layer was etched away from top of the bond pads

by using dry reactive ion etching. The physical dimensions and the quality of the fabricated gold nanodiscs fabricated on top of the CMOS chip were measured by SEM which showed that the quality of the discs fabricated on top of CMOS chip is as good as those fabricated on the glass substrate. A microscopic image (x100) of the gold nanodisc array fabricated on top of the PD is shown in the Figure 5a (encircled in black).

The CMOS PD chip with integrated gold nanodiscs was mounted on the PGA-120 chip carrier purchased from Spectrum Semiconductor Materials, USA. The chip was wire bonded to provide electrical connections and was packaged by an epoxy (EPO-TEK 302-3M epoxy) supplied by Epoxy Technology, USA to allow performing experiments with aqueous solutions. An encapsulated ring was attached to contain the aqueous solutions on top of the chip. The packaged chip with an encapsulated ring is shown in Figure 6a.

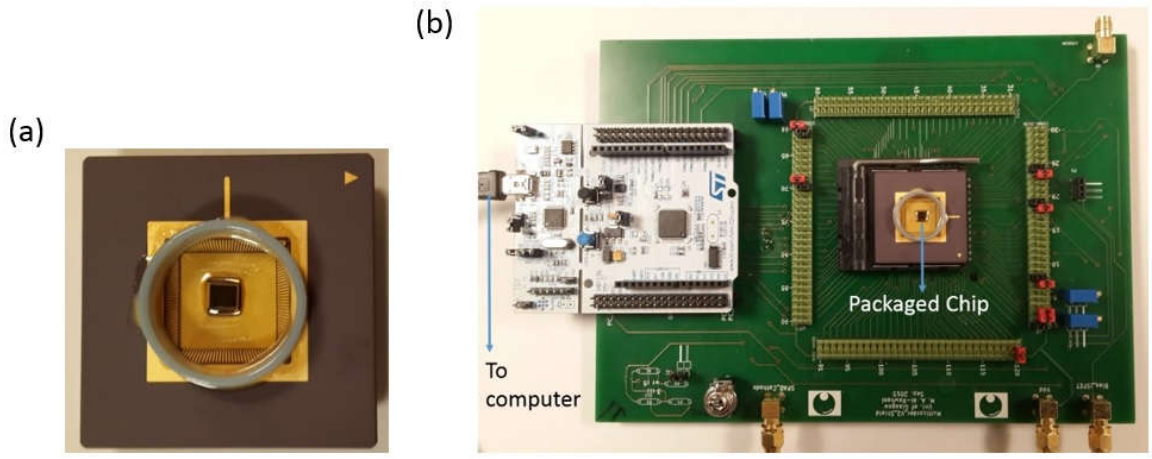

Figure 6: (a) Packaged CMOS chip with integrated gold nanodiscs. The encapsulated ring is attached to perform experiments with aqueous solutions. (b) Photograph of complete sensor system.

An instrumentation system was created which consisted of a laptop, ARM mbed Integrated Development Environment STM32 Nucleo-F334R8 board from STMicroelectronics UK, a custom printed circuit board from Newbury electronics, UK and the fabricated chip. The chip was operated with 3.3 V supplied by a power supply. The operation of the sensor system was controlled by LabView (National Instruments, UK) which was programmed to record the output voltage of the PD in real time and in a synchronous manner. The photograph of complete sensor system is given in Figure 6b.

6. EXPERIMENTAL RESULTS OF INTEGRATED SYSTEM AND DISCUSSION

6.1 Optical Reflection spectrum

To measure the resonance response of the gold nanodiscs fabricated on top of the CMOS chip, a reflection measurement was carried out by using the same commercial microspectrometer setup used for transmission measurements of the glass slide samples discussed in section 3.2. The optical reflection spectrum was measured prior to attaching the chip to the chip carrier. The reflection measurement of the gold nanodiscs integrated with the CMOS chip is shown in Figure 7. From the reflection spectrum it can be seen that the resonance wavelength of the gold nanodiscs integrated with the CMOS chip is at 750 nm, similar to resonance wavelength of the nanodiscs fabricated on top of glass slides. However, the reflection spectrum is noisy due to the presence of Fabry-Perot fringes generated by back reflection of the optical signal from multilayers of the CMOS chip.

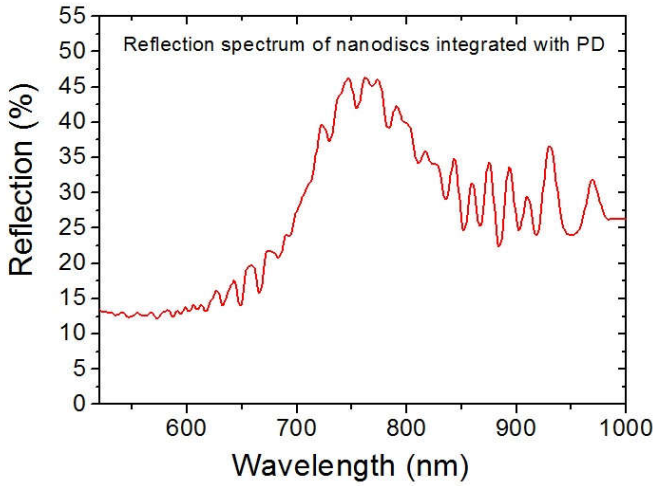

Figure 7: Experimental reflection spectrum of the gold nanodiscs integrated with the CMOS PD. The Fabry-Perot fringes superimposed on the spectrum arise due to back reflection of light from different layers of the CMOS chip.

6.2 Electrical Spectrum

The electrical spectrum (output voltage of the PD as a function of wavelength of incident light) of the CMOS PD was measured by scanning the wavelength of the incident light using a monochromator with a halogen lamp as the input light source. The electrical spectrum of the CMOS PD with and without integrated gold nanodiscs is shown Figure 8. A dip at around 780-825 nm in the electrical spectrum of PD integrated with gold nanodiscs can be observed which is absent in the output voltage spectrum of the PD without discs and hence corresponds to the plasmonic resonance of the integrated gold nanodiscs. The dip observed in the electrical spectrum is at longer wavelengths than the resonance wavelength of the gold nanodiscs because the electrical spectrum presented in Figure 8 is a convoluted response of the monochromator and PD responses.

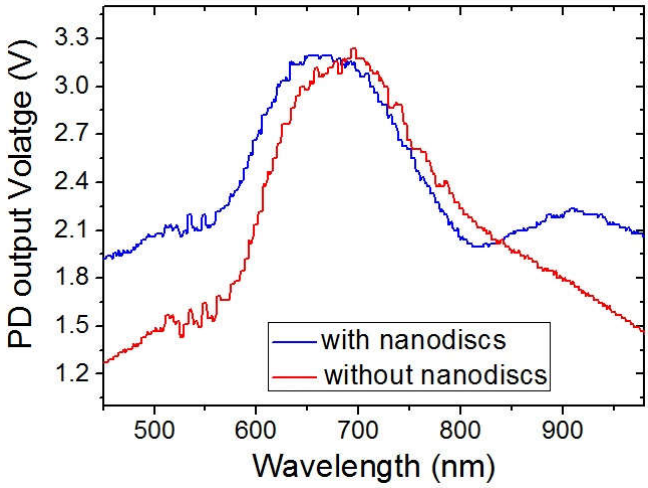

Figure 8: Output voltage spectrum of the PD with (blue curve) and without (red curve) gold nanodiscs. The valley around 780-825 nm in the electrical spectrum of the PD with integrated gold nanodiscs corresponds to the resonance of the gold nanodisc arrays.

It is noted that the dark current in the PD with integrated gold nanodiscs is higher compared to the PD without discs. This is perhaps due to post processing of the CMOS chip to integrate gold nanodiscs which involves multiple high energy e-beam exposures which can create defect centers in the active area of the PD causing an increase in the dark current.

6.3 Sensitivity analysis of the integrated system

To gauge the performance of the plasmonic sensor monolithically integrated with the CMOS PD different concentrations of glycerol were applied on top of the gold nanodisc structures and corresponding changes in the output voltage of the PD were measured. The input wavelength was fixed at 815 nm which is the minimum voltage point in the electrical spectrum caused by the resonance of the gold nanodiscs as shown in Figure 8. First, the refractive index was changed from 1.0 (air) to 1.33 (water) and then it was changed systematically in smaller steps by introducing different concentrations of glycerol. The increase in the refractive index causes a red shift of the resonance wavelength which is read directly as a change in the output voltage of the PD as shown in Figure 9 (black curve). A 10 % change in glycerol concentration ($\Delta n \approx 0.011$) causes a change of PD output voltage by 0.063 V in our integrated system. Hence, the electrical sensitivity of the integrated sensing system is measured to be 5.8 V/RIU for different concentrations of glycerol. On the other hand the change of refractive index by introducing different analytes does not change the output voltage of the PD which does not have gold nanodiscs integrated on top of it. The comparison of the output voltage responses of the PD with and without gold nanodiscs proves that the change in PD output voltage is caused by the change in optical intensity impinging on the PD due to the resonance wavelength shift of the array of gold nanodiscs. The comparison also shows that the effect of absorption or signal drift is negligible in our sensing system.

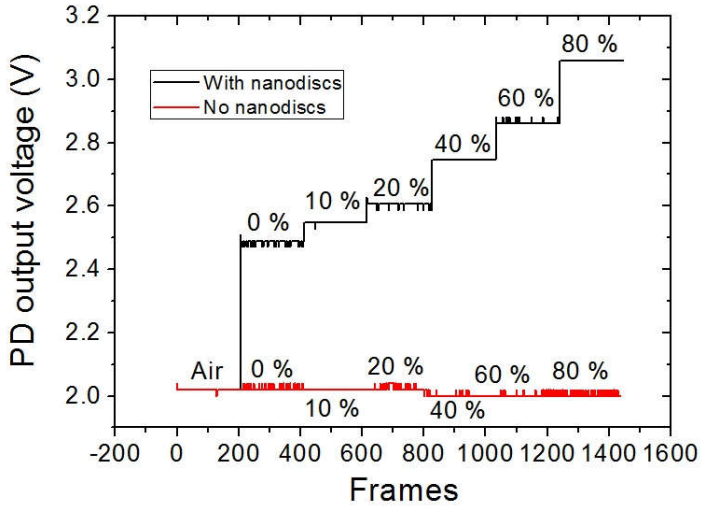

Figure 9: Electrical readout of the sensor system. The output voltage of the PD with integrated gold nanodiscs changes with application of different concentrations of glycerol (different refractive indices). On the other hand the output voltage of the PD without gold nanodiscs stays constant. In all experiments the wavelength of incident light was kept constant at 815 nm.

7. CONCLUSIONS

By monolithic integration of an array of gold nanodiscs with CMOS PDs we have demonstrated a compact nanophotonic sensor system having direct electrical read out. By doing so we have eliminated the need of using an optical spectrum analyzer for measuring nanophotonic sensors which is an important step towards making the use of nanophotonic sensors practical in everyday life. The measured optical sensitivity of an array of gold nanodisc array is 275 nm/RIU which translates to an electrical sensitivity of 5.8 V/RIU. The performance of the device can be improved further by integrating nanophotonic sensors having more optimized design and composed of different materials.

8. ACKNOWLEDGEMENT

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