New Trends in Design and Development of Optical Nano-Biosensors

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Abstract -- **Nanotechnology is currently playing a significant role in the development of biosensors. The sensitivity and performance of biosensors improves drastically by incorporating nanomaterials and adopting new signal transduction technologies. With the rapid development of tools and fabrication processes , nanoscale sensors capable of interacting with extremely small molecules have been developed. These advancements are important since such biosensors cater to research sectors where detection of low concentration analyte is desired. Furthermore, the use of highly sensitive surfaces such as biomolecule-functionalized surfaces can boost the specificity of the detection system. At the same time, reproducibility problems may arise besides increased complexity.**

In the current scenario, several nanobiosensor architecture-based mechanical devices, optical resonators, functionalized nanoparticles, nanowires, nanotubes, and nanofibers are being used. With the rapid advancements in the nanobiosensor technology, more refined and reliable lab-on-a-chip devices for rapid screening of a wide variety of analyses at low cost are in pipeline. More specifically, nanomaterials such as carbon nanotubes, magnetic nanoparticles , gold nanoparticles and quantum dots have been actively investigated for their applications in biosensors, which have become a new bridge between biological detection and material science. This paper reviews the characteristics of Optical nano-biosensors and discusses a Novel Technique of embedding an NMOS Phototransistor on a silicon photonics platform the various nanostructure-based biosensors with a general perspective of design optimization.

Keywords: Nanomaterials, Nanobiosensor, carbon nanotube-based biosensors.

I. INTRODUCTION

A biosensor is a device that uses specific biochemical reactions mediated by isolated enzymes, immune systems, tissues, organelles or whole cells to detect chemical compounds usually by electrical, thermal or optical signals (McNaught and Wilkinson 1997). Beginning of biosensors may be dated to 1962, when Clark, known as the father of the biosensor concept published an experiment in which glucose oxidase (GOX) was entrapped at a Clark oxygen electrode using dialysis membrane (Clark Jr. and Lyons 1962).

As bio-components, an enzyme, antibody, nucleic acid, lectine, hormone, cell structure or tissue can be used. Its role is to interact specifically with the target analyte and the result of biochemical reaction is consequently translated through a transducer into an equivalent measurable signal. More technically, biosensor is a probe that integrates a biological body with an electronic component to yield a measurable signal. In this, a bioreceptor is combined with a suitable transducer which produces a signal after interaction with the target molecule of interest.

These biosensors consist of three components: the biological recognition element, the transducer and the signal processing electronics. The amplifier in the biosensor responds to the small input signal from the transducer and delivers a large output signal that contains the essential waveform features of an input signal.

II. BACKGROUND AND MOTIVATION

Nanotechnology is a new branch of science that deals with the generation and alteration of materials to nanosize (10^{-9} m). Nanomaterial has large surface area when compared to same mass in larger form. This makes it highly reactive and has an effect on the material's strength and electrical properties.

Nano-Biosensors have become an important ingredient in many scientific fields including clinical diagnostics, medical developments, illicit drug detection, food quality and safety, and environmental monitoring The research in biosensor technology shows a constant increase in relation to the various nanomaterials with the interest to be implemented either into transducers or receptors operation parts, so as to enhance their multidetection capability and sensitivity. There is a big demand for fast, reliable and low-cost systems for the detection,

monitoring and diagnosis of biological molecules and diseases in medicine.

For the past years, a number of different natural and artificial biological elements have been used in biosensors; the most important ones being enzymes, thin films etc The presence of the biological element makes the biosensor systems extremely specific and highly sensitive, giving an upper edge over the conventional methods. In enzyme based biosensors, the biological element is the enzyme which reacts selectively with its substrate.

III. MAIN CHALLENGES

In recent years, Optical interconnects have exhibited tremendous competency for replacing electrical wires for both on-chip and off-chip communications. The challenge posed here is to develop low energy per bit receivers, of the order of 10 fJ/bit or less in order to support on chip communication . To achieve this, low capacitance photodiodes integrated with low capacitance receiver circuits are required. Many groups have worked on creating low capacitance (1–10 fF) photodiodes on waveguides. Furthermore, emphasis has been laid upon integrating low-capacitance photodiodes through either wire-bonding or monolithic integration with CMOS receiver circuitry.

Biosensor designing has currently become an area of utmost significance among researchers from various fields such as; physics, chemistry, biology, engineering and medicine. Their focus lies in developing, constructing and manufacturing new sensing devices to get more efficient and reliable and accurate information regarding the specimen under investigation.

Advances in biosensor technology and signal amplification have led to highly sensitive detection of pathogen-specific and host immunity biomarkers. However, sample preparation is increasingly recognized as the critical bottleneck in translating biosensors from the laboratory to clinics .Hence to design a highly accurate optical sensor is a big challenge.

IV. OPTICAL BIOSENSORS

The basic objective of optical biosensor is to produce an electronic signal which is proportional in magnitude or frequency corresponding to the concentration of a specific analyte or group of analytes, to which the biosensing element binds.

Optical biosensors are powerful alternative to conventional analytical techniques, for their particularly high specification, sensitivity, small size, and cost effectiveness.

The research and technological development of optical biosensors have experienced an exponential growth during the last decade because this technology has a great potential for the direct, real-time and label-free detection of many chemical and biological substances. Deposition techniques such as screen printing and ink-jet printing allow printing of materials at very high precision and speed, producing large numbers of inexpensive and reproducible biosensors.

The technology of integrated optics allows the integration of several passive and active optical components onto the same substrate, allowing the flexible development of minimized compact sensing devices, with the additional possibility of fabrication of multiple sensors on one chip. The advantages of optical biosensors are their speed, the immunity of the signal to electrical or magnetic interference, and the potential for higher information content (spectrum of information available) but the main drawback can be the high cost of some instrumentation.

Although promising developments of optical biosensors are being reported, but there are not many reports on applications of optical biosensor in practical field . The advantages of the optical sensing are significantly improved when this approach is used in an integration scheme At present, with the threat of bioterrorism, the development of faster, reliable, accurate, portable, and low-cost biosensors has become more important.

Figure 1 shows the architecture of an optical biosensor.

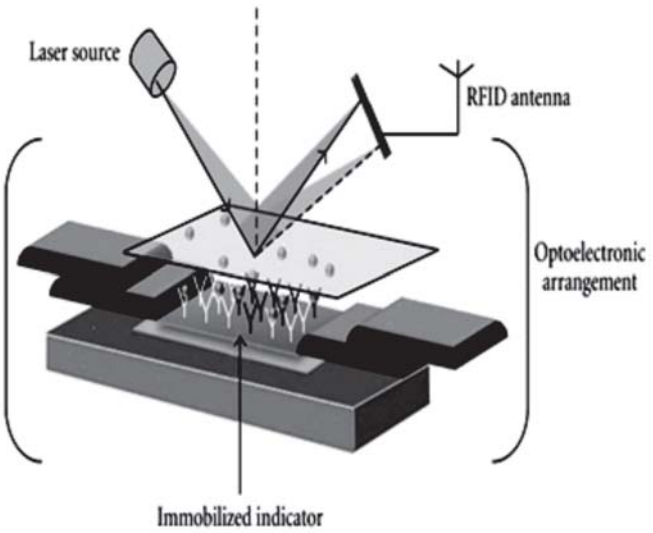

Figure 1. Architecture of an Optical Biosensor.

V. EMBEDDED NMOS PHOTOTRANSISTOR INTEGRATED ON A SILICON PLATFORM

In this design procedure, the phototransistor is fabricated with a modified NMOS process flow.It is further recrystallized during the source/drain Annelation process.The resultant devices has effective dimensions of 1 μm channel length and 8 μm channel width which increases the responsivity to 18 A/W at 1550 nm with around 580 nW.

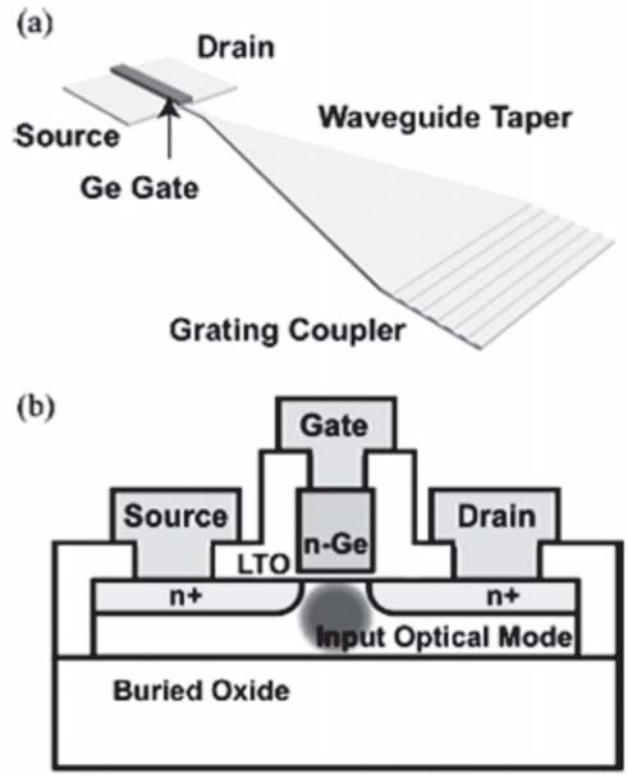

Figure 2. (a) 3-D Schematic drawing of the photoMOSFET with integrated silicon photonics components. (b) Schematic cross-section of the photoMOSFET

This device is a self aligned NMOS with a Silicon channel and a Germanium gate. The light in the phototransistor is automatically coupled into the Germanium gate due to its higher refractive index.

In this model body doping is chosen for simplicityyielding a maximum doping ($10^{17}cm^{-3}$) width of 105nm. In generate optimal photoresponse, a moderate doping concentration of Germanium atoms is selected.

VI. OPERATION

When the device is not illuminated,the internal is in reverse biased and no no current flows through it since the device is a photodiode having a cathode coupled with the gate contact.

When the device is illuminated, the device behaves as a solar cell working in the open circuit mode. The voltage so developed adds to the gate voltage. Due to this the effective voltage of the gate becomes higher.

Hence the photocurrent developed at the drain terminal may be computed as:

$$I_d = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_g + V_{photo} - V_T)^2 .$$

where

C_{ox} - Capacitance of the oxide layer on the gate.
V_g Gate Potential, V_{photo}-Photo voltage,
V_T-Threshold voltage, L-Gate length, W-Gate width.

The total voltage so induced is also affected by the quantum efficiency of the leakage current of the internal diode.

VII. ELECTRICAL AND OPTICAL RESPONSE

Optical characterization:

In order to generate the optical responses, passive silicon photonics components were first developed on the chip. For this purpose, an angled single mode fiber was used to investigate two back-to-back grating couplers using waveguides of different lengths. This method is analogous to the electrical transmission line measurement for contact resistance. The measured insertion loss for each grating and

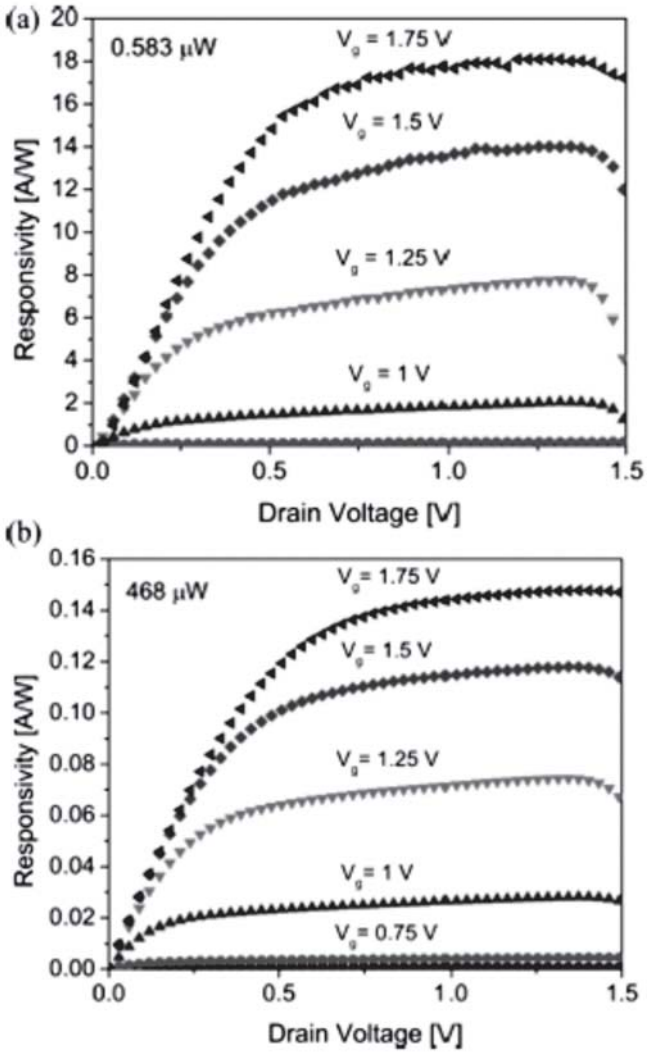

Figure 3. (a) Measured responsivity with 0.583 μW of incident power. (b) Measured responsivity with 468 μW of incident power.

taper was 20 dB at 1550 nm. This value has been calculated by dividing the total back-to-back insertion loss by two.

This results in high insertion loss which is due to the gratings being slightly red-shifted due to an exposure error during the grating lithography step. Additionally, this results in high waveguide loss due to incomplete removal of germanium and aluminum during the etching steps. The grating and taper insertion loss is taken into account during all the optical measurements. so that the reported incident power is the actual power incident on the device from the single mode waveguide.

Electrical characterization: The electrical attributes are revealed by plotting Drain current against Drain voltage and Gate voltage both for dark and illuminated modes. The responsivity of the device may be evaluated by dividing the photocurrent by the reported incident power.Identical to a usual transistor, the fabricated pototransstor develops a photocurrent which is a function of the applied bias.Higher gains may be obtained by suitably increasing the drain voltage.

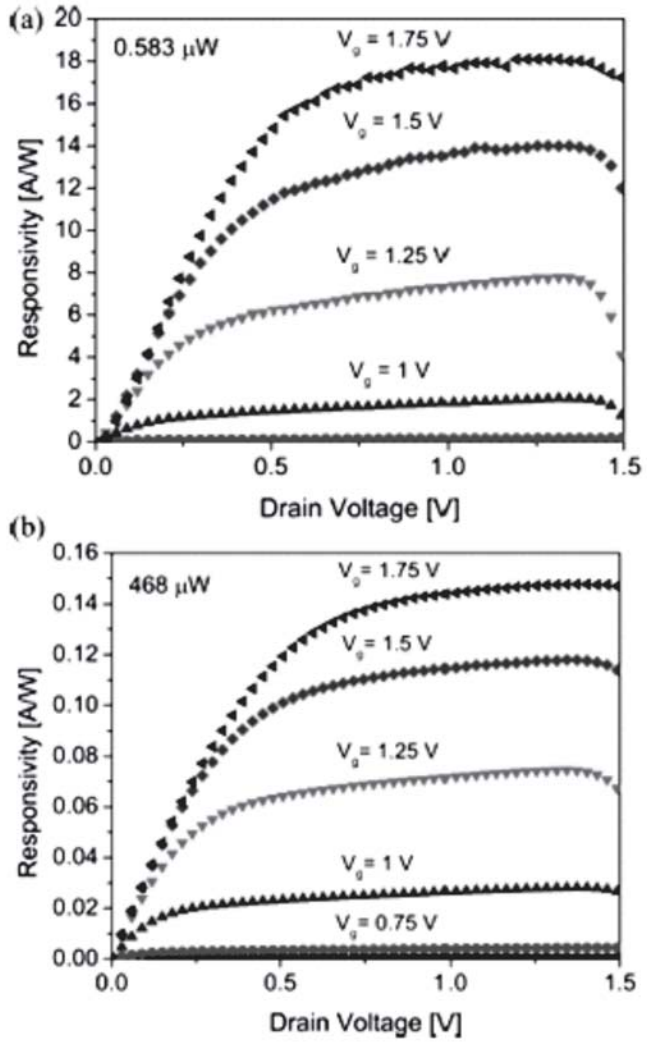

Figure 4. (a) Drain current as a function of drain and gate voltage both in the dark and with 468 μW of illumination. (b) Drain current as a function of gate voltage at a drain voltage of 1 V (dark and with 912 μW of illumination).

The responses are measured for different values of optical input power levels.

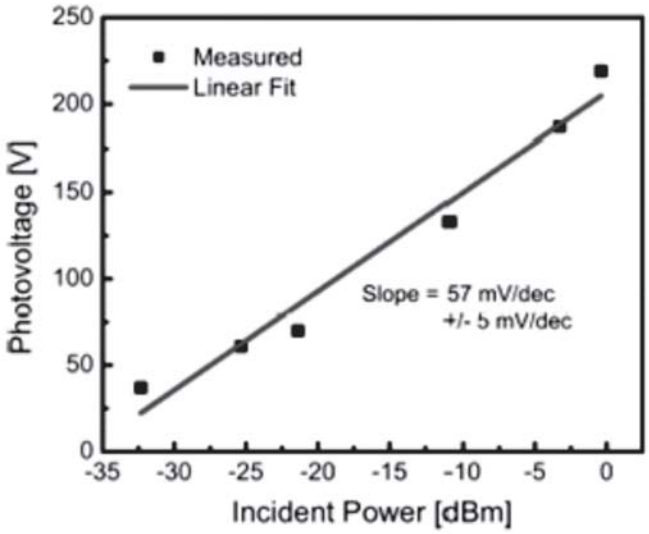

Figure 5. Plot of Photovoltage as a Function of Incident power.

VII. CONCLUSION

The former part of this paper has taken into account the growing need for design and development of stable, reliable, highly selective and efficient nano-biosensors. Furthermore, strong emphasis has been laid upon use of nanoscaling techniques.

The latter part of the paper has reviewed a novel technique for design and development of an optical nanobiosensor based device using a phototransistor with a higher scaling factor. It has been established that a direct integration of the device with Silicon photonics can yield higher optical power with efficient light absorption. It has been further established that higher gains may be obtained by increasing the drain voltage, right upto the saturation point.

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