Electrical and Optical Nanosensors

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ABSTRACT

Electrical and optical nanosensor device platforms for biochemical analytics and biomedical diagnostics have been developed. The nanosensors employ nanobelt, nanogap and photonic wire structures fabricated on silicon-on-insulator (SOI) wafers in order to facilitate CMOS compatible fabrication processing. In SOI wafers, a thin silicon layer is separated by a silicon oxide layer from the bulk. An optimized dry etching process allows the removal of both the top silicon layer and the SiO_2 in order to yield the nanobelt and nanowire shapes. The SiO_2 layer is finally removed, which results in free standing nanobelts and nanogaps. The optical nanosensors are based on Si-photonic wires and slot-waveguide geometries and incorporate Mach-Zehnder-interferometer structures. Simulation tools for the calculation of the sensitivity and the mode behavior as a function of the waveguide geometry were developed and used in order to optimize the sensing performance.

Keywords: nanosensors, nanogaps, nanobelts, silicon photonic wires.

1 INTRODUCTION

Triggered by various applications like industrial process control, environmental monitoring, health and safety, there is an increasing demand for sensor instrumentation. Highly sensitive devices have to be developed for applications in biochemical and biomedical analysis, such as electronic noses for gas sensing or biosensors for DNA detection. To fulfil the permanently increasing specifications with respect to higher sensitivity, selectivity and power consumption, efforts to enhance the performance by means of micro- and nanofabrication technologies are in progress.
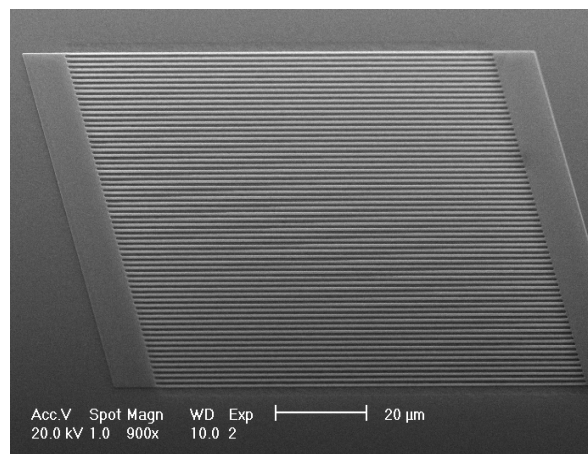
2 NANOSENSORS

Nanosensors for chemical and biochemical substances are a very attractive application area. Nanosensors based on nanobelts and nanowires are smaller, more sensitive, demand less power, and react faster than their macroscopic counterparts. Arrays of nanobelts and nanowires could provide real-time information regarding the concentration of a specific analyte as well as its spatial distribution [1-5].

The integration of nanoelectronics and biotechnology requires interfaces that are compatible with microelectronics fabrication processing methods and provide the required stability when exposed to biological environment. In order to meet these requirements and with respect to practical fabrication and commercialization of the devices, well-established processes based on CMOS technology are favorable. Both electronic as well as optical nanosensors based on silicon are therefore relevant devices for high sensitive detection applications.

2.1 Electrical Nanosensors

The electronic nanosensors are based on nanobelt, and nanogap structures. Nanobelt structures have been fabricated on silicon-on-insulator (SOI) wafers. In SOI wafers, a thin silicon layer (230 nm) is separated by a silicon oxide (SiO_2) layer (380 nm) from the bulk. An optimized dry etching process, based on reactive ion etching, allows the removal of both the top silicon layer and the SiO_2 in order to yield the nanobelt shapes. The SiO_2 layer is finally removed with hydrofluoric acid, which results in arrays of free standing nanobelts as shown in Fig. 1. The left and right areas are for the contact pads,

which electrically connects several nanobelts in parallel.

Figure 1: Scanning electron microscope image of silicon nanobelt array.

The operation of the nanosensor is based on a change in the electrical conductance through the nanobelts. In the next step the surface of the nanobelt will be modified by specific functional layers in order to achieve a specific selectivity for gas sensing applications.

Fig. 2 images the nanogaps under the etched, free standing nanobelts, which will be utilized for DNA

detection. The width of the nanogaps, however, has to be further decreased for this specific application.
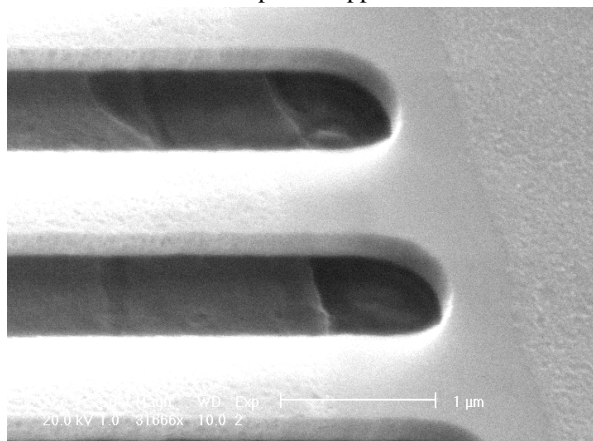

Figure 2: Scanning electron microscope image of single silicon nanobelts. The image visualizes the nanogaps under free standing nanobelts.

2.2 Vertical Nanogaps

DNA sensing has become required for applications in many fields, such as medical treatments, foods and environments. Electrical DNA nanosensors appear the most promising devices and DNA chips with nanogaps as sensing structure have been proposed and realized. The operation principle is based on bridging the nanogap between two electrodes with DNA, which results in electrical conductivity between the electrodes. The measurement of electrical conductivity of DNA is highly sensitive. To detect electric currents through DNA directly, the gap between electrodes should be narrower than 50 nm., otherwise the currents become too small [6,7].

Lateral nanogaps with electrodes separated at a distance of a few tens of nanometers can be fabricated only with sophisticated electron beam lithography. The reproducibility of lateral nanogaps, however is difficult to be achieved.

Another possibility for the realization of nanogap sensor devices relies on the fabrication of nanometer-sized gaps in semiconductor layer systems. The basic structure of a nanogap device has been already achieved by under etching the electrical nanobelt structures, as shown in Fig. 2, where the width of the gap is 380 nm, which can be adjusted by the SiO_2-layer thickness of the SOI-wafer.

A vertical nanogap device structure has been fabricated from two stacked silicon layers with a thin SiO_2-layer in between, where the width of the gap depends only on the thickness of the SiO_2-layer. A control of the layer thickness can be well achieved, therefore this approach is very reliable with respect to reproducibility. The final structuring of the device can be performed with standard photolithography over large areas, no sophisticated and

expensive lithography have to be used for the fabrication of the nanogap device.

In order to fabricate a nanogap in the order of tens of nanometers, a SOI wafer has been oxidized to achieve a SiO_2-layer of 20 nm thickness. The wafer has been cleaved into single samples, which have been bonded face-to-face in order to sandwich a 40 nm SiO_2-layer between two Si-layers forming the electrodes. The resulting layer system is a silicon substrate, a 380 nm SiO_2-layer, a 230 nm Si-layer, another 40 nm $.SiO_2$-layer and a Si-top layer. The bonded wafer has been cleaved and etched with hydrofluoric acid in order to demonstrate the fabricated nanogap. The resulting nanogap is shown in Fig. 3, the width of the gap is 40 nm and can be adjusted by the parameters used for oxidation before the wafer bonding process.
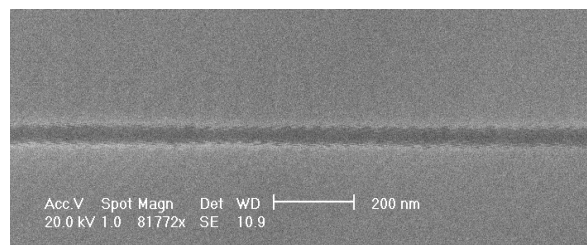

Figure 3: Scanning electron microscope image of the vertical nanogap between two Si-electrodes.

The final processing of a functional nanogap device will include an additional process step before the wafer bonding: H+-ions will be implanted to a certain depth within the Si-substrate in order to perform a smart-cut-process step after bonding the wafer face-to-face. This will result in a thickness of the Si-top layer in the order of 200 nm.

2.3 Optical Nanosensors

Novel photonic devices are promising for innovative applications in the field of sensor technology [8-10]. In planar integrated waveguide devices light is confined in a waveguide layer that has a higher refractive index than the surrounding cladding layers. The light propagates inside the waveguide layer. A part of the optical field penetrates into the cladding layers. These evanescent fields can be exploited for sensing changes in the refractive index of the cladding layer.

Photonic nanosensors utilize silicon as ultra-high index contrast material. The principle of an optical nanosensor based on silicon photonic wires and a Mach-Zehnder interferometer geometry is shown in Fig. 4. For biosensing applications in an aqueous analyte, for example, the reference Si-branch (right) is isolated from the environment, while the sensing branch (left) is coated with a functional biosensitive layer.
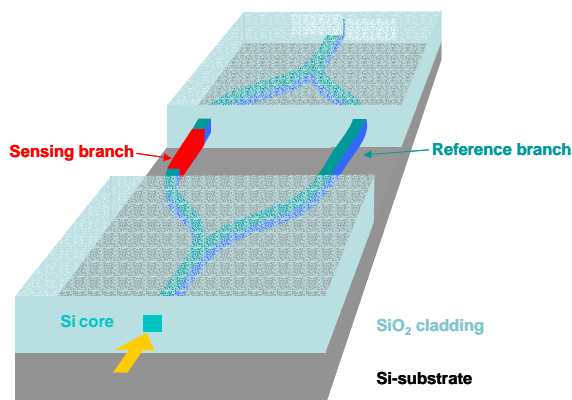
Figure 4: Principle of an optical nanosensor based on silicon photonic wires and a Mach-Zehnder interferometer geometry.

Only a specific type of molecules can be captured by the biosensitive layer. The capturing process changes the refractive index of the surface layer and thus modifies the optical characteristics of the wave guided along the Si-photonic nanowire. This change of refractive index can be detected in a highly sensitive manner by the Mach-Zehnder-interferometer waveguide structure. The operation wavelength of the device is 1.55µm, standard laser diodes and a fiber optical setup are used for coupling the light into the Si-photonic wire.
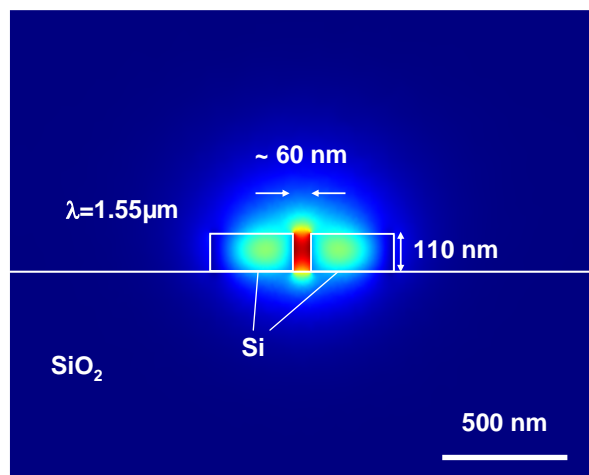

Figure 5: Simulation of a slot-waveguide configuration. More than 50% .of the light intensity is guided in the slot which results in an opitimized interaction between the sensing light and the analyte.

The performance of the optical sensing device strongly depends on the geometry of the photonic nanowire. The sensing performance can be optimized by choosing a slot-waveguide geometry in the sensing branch. Slot-waveguides allow for a stronger interaction between guided light and surrounding media. The fabrication of these structures requires sophisticated e-beam lithography, therefore the geometry has to be well designed before the fabrication process.

Simulation tools for the calculation of the sensitivity and the mode behavior as a function of the waveguide geometry were developed and used in order to optimize the sensing performance. The simulation result of optimized slot waveguide geometry is shown in Fig. 5. The thickness of the single Si-nanowires is 110 nm, the width 220 nm, while the gap in between is as small as 60 nm. Most of the light intensity is guided in the slot between the single Si-photonic waveguides, which increases the sensitivity of the device. In the next step the device will be fabricated by means of e-beam lithography in order to demonstrate the sensing performance.

3   OUTLOOK

Electrical and optical nanosensor device platforms based on SOI-wafer processing have been successfully fabricated and demonstrated. The device platforms have to be adapted to the desired applications, such as biochemical analytics and biomedical diagnostics. Therefore specific functional layers will be applied to the nanosensor surfaces in the next steps. For example thin nanocrystalline SnO_2 layers will be applied on the nanobelt structures in order to achieve a sensitivity for gases, while bio molecule layers will be applied for DNA-detection.

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