

SiN_x/SiO₂ STACKED SENSITIVE THIN FILM FOR ISFET-BASED CHEMICAL AND BIOCHEMICAL SENSORS

Preparation and Characterization of the Stacked Thin Films and Sensors

J. F. Souza^{1,2,3}, M. B. Lima⁴, I. Doi^{1,2}, P. J. Tatsch^{1,2}, J. A. Diniz^{1,2} and J. L. Gonçalves³

¹School of Electrical and Computer Engineering, University of Campinas, Av. Albert Einstein 400, Campinas, SP, Brazil

²Center for Semiconductor Components, University of Campinas, R. João Pandiá Calógeras 90, Campinas, SP, Brazil

³Center for Information Technology Renato Archer, Rod. D. Pedro I (SP – 65) Km 143, 6, Campinas, SP, Brazil

⁴Superior School of Sciences of the Health, University of Amazonas, Av. Carvalho Leal, 1777, Manaus, AM, Brazil

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Abstract: In this work, nitrogen rich SiN_x thin film was deposited on SiO₂/p-Si (100) substrate by low pressure chemical vapour deposition (LPCVD). The film was physically characterized using techniques such as Fourier transform infrared spectroscopy (FTIR), atomic force microscopy (AFM) and ellipsometry. The biocompatibility of such film was investigated by FTIR. Using a set of metal insulator semiconductor field effect transistors (MISFETs) and ion sensitive field effect transistors (ISFETs) fabricated, electrical characteristics and sensing properties were investigated. The biocompatibility of the SiN_x film and the electrical quality of the SiN_x/SiO₂/p-Si interface obtained suggests that SiN_x/SiO₂ is an adequate insulator on ISFET based chemical and biochemical sensors.

1 INTRODUCTION

LPCVD Si₃N₄ films are used as the sensitive material in miniaturized ISFET-based chemical and biochemical sensors. Such devices have been used for example for further surface modifications allowing for antigen-antibody biosensor applications. In vivo studies classify Si₃N₄ as a biocompatible material (Gustavsson et al., 2008). The first ISFET was applied by Bergveld (Bergveld, 1970) to a biosensor for measuring ion concentration in nerve tissues. The latest investigations related to the ISFET-based biosensor are extended to immunosensing (Schenck, 1978, Schöning and Poghossian, 2002) and DNA hybridization sensing (Souteyrand et al., 1997, Pouthas et al., 2004). Ultrasensitive detection of biomolecules using various types of one-dimensional nanostructures such as carbon nanotubes (Villamizar et al., 2008), graphenes (Cheng et al., 2010) and nanowires (Knopfmacher et al., 2010) has attracted broad research interest during the past decade due to their high surface-to-volume ratio. An important parameter, the slope of characteristic, is directly related with sensitivity of the sensor. These aspects

have not been yet convincingly reported, for this reason, this work reports the use of SiN_x/SiO₂ stacked sensitive thin films that are biocompatible and present high quality of the electrical interface, increasing the sensitivity and making possible a direct electrical detection of charged molecules.

2 EXPERIMENTS

2.1 SiN_x/SiO₂ Stacked Sensitive Thin Film Preparation

The (100)-orientated 1-10 Ω.cm p-type silicon wafers were used as substrates. The 5 nm thick thermally grown silicon oxide (SiO₂) film was prepared using a conventional furnace at 1000 °C for 1 minute, in a high purity oxygen atmosphere. Then, the SiN_x layer, a sensing membrane, was deposited by LPCVD in a SiCl₂H₂/NH₃ gas mixture atmosphere at 740 °C. The base and work pressure of the chamber were 10 mTorr and 0.57 Torr, respectively. The flow rate of SiCl₂H₂ was fixed at 23 standard cubic centimeters per minute (sccm), while the flow rate of NH₃ was 60 sccm. All

deposition parameters are shown in Table 1.

Table 1: Parameters for the deposition of SiN_x film.

SiCl ₂ H ₂ flow rate	23 sccm
NH ₃ flow rate	60 sccm
Temperature of the substrate	740 °C
Base pressure	10 mTorr
Work pressure	0.57 Torr
Deposition rate	27 Å/min

2.2 Immunoglobulin's Self-assembled Monolayer (SAM) Preparation

Figure 1 shows a schematic diagram of the method used to prepare the substrates (functionalization). The substrates were cleaned using a standard RCA wet process. The 3-Aminopropyltriethoxysilane (APTS) coating was carried out in a solution of 5% APTS in toluene for 6 h, at 80 °C. The non-adsorbed APTS was removed by rinsing the substrate with toluene and ethanol and dried with N₂ gas. The APTS-modified substrates were baked in an oven at 110 °C for 16 h. To form the immunoglobulin's SAM (Figure 1, immobilization), the substrates coated with APTS were immersed into a solution of ethylcarbodiimide (EDC), 2 mM, N-hydroxysuccinimide (NHS), 5 mM, and immunoglobulin - IgG, 1 µg/ml, at room temperature for 2 h, and then washed with phosphate buffered saline (PBS) of pH 7.2 and deionized water (18 MΩ).

2.3 MISFET and ISFET Structures Fabrication

For the MISFET and ISFET the SiN_x/SiO₂ stacked sensitive thin film were used as gate dielectric on p-type (1-10 Ω.cm) Si (100) substrate. The substrates were cleaned using a standard RCA wet process. The critical steps in this fabrication procedure are as follow:

- 1) Thermal gate oxide: 50 Å;
- 2) SiN_x deposition by LPCVD: 300 Å;
- 3) SiN_x dry etching and oxide wet etching of the source and drain regions;
- 4) Al etching of gate electrode; and
- 5) Entire device coated with insulating layer to eliminate ionic short circuits due to exposure to solutions.

2.4 SiN_x Layer Characterizations

The SiN_x thin films used in these studies were

characterized by FTIR (infrared spectra with 32 scans and 4 cm⁻¹ resolution), AFM in contact image mode (surface morphology), and ellipsometry (film thickness and refractive index).

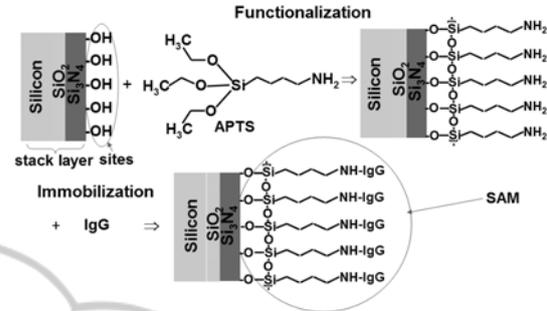


Figure 1: Schematic diagram of the preparation of the substrates (functionalization) and formation of the immunoglobulin's SAM (immobilization).

2.5 IgG's SAM Characterization

After immunoglobulin's SAM preparation, Fourier transform infrared spectra were performed. All spectra are collected with 32 scans and 4 cm⁻¹ resolution.

2.6 Measurements Setup

In order to study electrical and sensing properties, current-voltage (I_{DS} - V_{GS}) and current-time (I_{DS} -time) of MISFETs and ISFETs structures were measured by a semiconductor parameter analyzer Keithley 4200-SCS. The gate voltages were applied to an aluminium metal gate of MISFETs and a gold reference electrode for ISFETs.

3 RESULTS AND DISCUSSION

3.1 Physical Characteristics of SiN_x Film

The FTIR spectrum of SiN_x (Figure 2) exhibits a clearly pronounced peak at 828 cm⁻¹ and smaller peak at 467 cm⁻¹, which are typical for the Si-N bond in amorphous silicon nitride (Beshkov et al., 2003). The deposition rate is 27 Å/min and the films have high refractive index $n = 2.0$ indicating that the films are nitrogen rich. The AFM image (Figure 3) shows the formation of very smooth and uniform SiN_x films, with average (Ra) and root mean square (Rrms) roughness of 0.31 nm and 0.46 nm, respectively.

3.2 IgG's SAM Characteristics

The characteristic vibrational peaks are mainly dominated by the protein constituents of the IgG's SAM (Figure 4). A vibration band assignment is done with the idea of the group frequencies of the various analytes present in the SAM. The spectral region $3600\text{--}3000\text{ cm}^{-1}$ comprises of C-H, O-H, and N-H stretching vibrations of the proteins. The prominent absorption peak at 3300 cm^{-1} is due to the N-H stretching mode (amide A) of proteins. The asymmetric and symmetric stretching C-H vibrations of methyl and methylene group are found to be present around $2930\text{--}2875\text{ cm}^{-1}$. The strong absorption band at 1650 cm^{-1} correspond to C=O stretching vibrations (amide I) whereas the vibration band at 1542 cm^{-1} is attributed as amide II arising of N-H bending vibrations strongly coupled with C-N stretching of proteins. The absorption peaks in the region $1400\text{--}1200\text{ cm}^{-1}$ arise due to the C-H deformation of methyl and methylene group of the proteins. The spectral region $1250\text{--}925\text{ cm}^{-1}$ is predominantly occupied by C-O-C asymmetric and symmetric vibrations of phospholipids of proteins (Sankari et al., 2010).

3.3 Electrical Properties of Devices

MISFET – Electrical characteristics of MISFETs including transconductance (G_m), current-off (I_{off}) and subthreshold swing (S_t) were calculated through drain-source current versus gate-source voltage ($I_{DS}\text{--}V_{GS}$) curves of the stack $\text{SiN}_x/\text{SiO}_2$ gate MISFET (Figure 5). The I_{off} extracted at $V_{GS}=V_T - 0.5\text{ V}$ was $2.17 \times 10^{-10}\text{ A}$. The calculated maximum transconductance of the stack $\text{SiN}_x/\text{SiO}_2$ gate MISFET was $1.4\text{ }\mu\text{S}$. S_t is the slope of V_{GS} versus $\log I_{DS}$. The S_t was obtained from the inverse of slope in subthreshold region and is 147 mV/dec to the stack $\text{SiN}_x/\text{SiO}_2$ gate MISFET. These values are acceptable for FET operation in an analog readout circuit.

SENSING PROPERTIES – For pH sensitivity calculation of the stack $\text{SiN}_x/\text{SiO}_2$ gate ISFET, the I_{DS} vs. V_{GS} , I_{DS} vs. V_{DS} and I_{DS} vs. time curves in saturation region were measured in standard pH buffer solutions (pH 4, 7 and 10) at room temperature. In Figure 6, the obvious linear shift of $I_{DS}\text{--}V_{GS}$ curves in different pH buffer solutions were shown. The pH response and sensitivity was 50 mV/pH ($I_{DS}=5\text{ }\mu\text{A}$), so a quasi-Nernstian response.

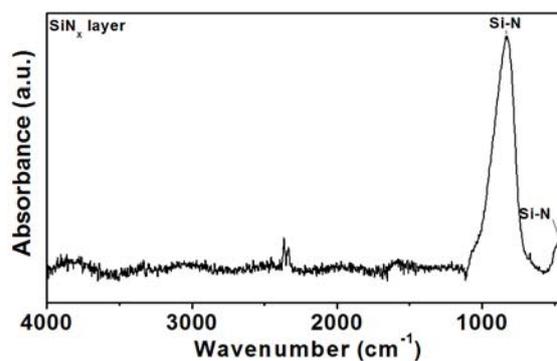


Figure 2: FTIR spectrum of SiN_x film deposited in LPCVD reactor at $740\text{ }^\circ\text{C}$ with SiCl_2H_2 and NH_3 .

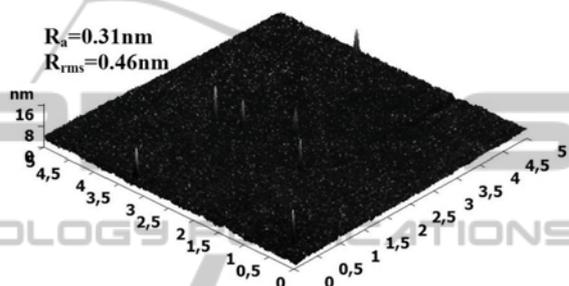


Figure 3: Surface morphology of SiN_x film on SiO_2 .

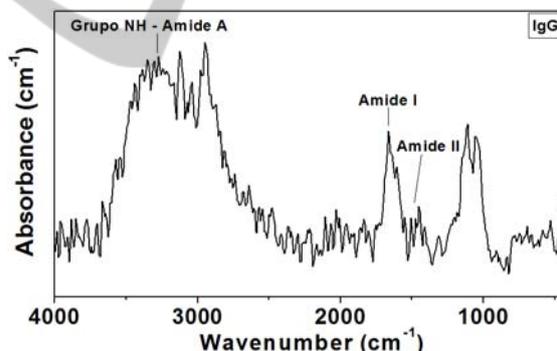


Figure 4: FTIR spectrum of immunoglobulin's SAM.

The behaviour of current in function of time was measured at constant drain-source and gate-source voltage ($V_{DS}=V_{GS}=2\text{ V}$). As can be seen in Figure 7 and 8, the device showed an increase in current when the pH value was increased. The pH sensibility was $1.24\text{ }\mu\text{A/pH}$. The linearity of the stack $\text{SiN}_x/\text{SiO}_2$ gate ISFET response is 97.4% in voltage mode and 99.4% in current mode. Therefore, both the pH responses are excellent in linearity. The characteristic curves of the stack $\text{SiN}_x/\text{SiO}_2$ gate ISFET shows the normal FET operation and exhibit the similar electrical characteristics as MISFETs.

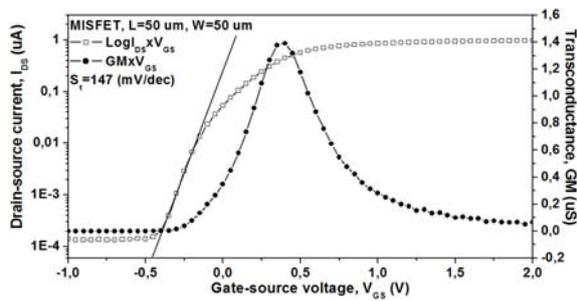


Figure 5: Log I_{DS} vs. V_{GS} and G_m vs. V_{GS} characteristics of the stack $\text{SiN}_x/\text{SiO}_2$ gate MISFET.

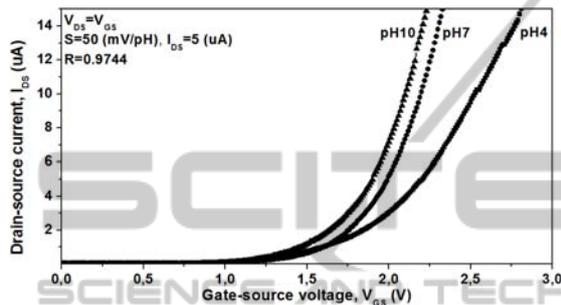


Figure 6: I_{DS} vs. V_{GS} curves of the stack $\text{SiN}_x/\text{SiO}_2$ gate ISFET measured at room temperature in standard pH buffer solutions (pH 4, 7 and 10).

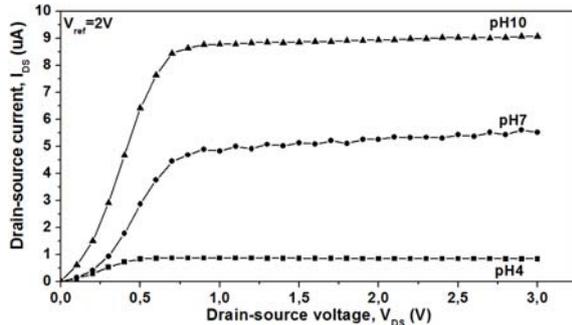


Figure 7: I_{DS} vs. V_{DS} curves of the stack $\text{SiN}_x/\text{SiO}_2$ gate ISFET measured at room temperature in standard pH buffer solutions (pH 4, 7 and 10).

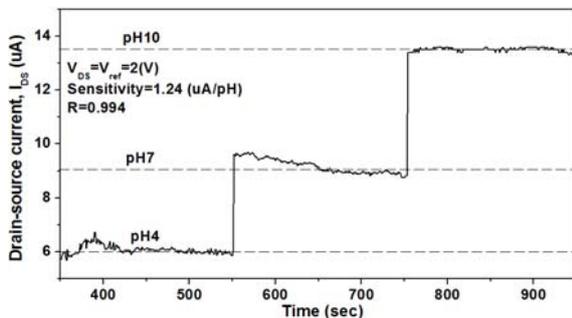


Figure 8: I_{DS} vs. time curve in saturation region, measured in standard pH buffer solutions (pH 4, 7 and 10) at room temperature ($V_{DS} = V_{GS} = 2V$).

4 CONCLUSIONS

In this study, stacked sensing membrane with LPCVD SiN_x on SiO_2 was used for ISFET-based chemical and biochemical sensors. The SiN_x obtained was very smooth and nitrogen rich. By fabricating and characterizing Immunoglobulin's self assembled monolayer we have demonstrated the biocompatibility of the films. Electrical and sensing properties were investigated by means of the stack $\text{SiN}_x/\text{SiO}_2$ gate MISFETs and ISFETs, respectively. The results showed that the MISFET exhibits good electrical characteristics. In regard to pH sensing properties analysis, the stack $\text{SiN}_x/\text{SiO}_2$ ISFET-based sensor presented high performance with almost Nernstian response (sensitivity of 50 mV/pH) and high linearity of 97.4% in voltage mode and 99.4% in current mode. The obtained results demonstrate therefore the feasibility of ISFET-based sensors for the detection of charged molecules.

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