A Biosensor Based on GaN Field Effect Transistor

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Abstract

Among the various techniques of biosensing, field effect transistor (FET) based detection of biological materials is interesting due to its label-free detection and rapid identification. Recently, GaN has been considered as a promising candidate for biosensor application due to its inertness to a chemical environment. In this work, AlGaN/GaN high electron mobility transistor (HEMT) wafer with a 2DEG mobility of 1300 cm^2/v-s and a sheet carrier density of 1×10^{13} cm^{-2} was used as a sensor platform. Ti/Al/Ni/Au was used as source and drain contacts and a Ni/Au contact were deposited for the gate electrode. Polydimethylsiloxane (PDMS) was used as an encapsulating agent. The DNA immobilization on the Au gate was carried out using thiol-based chemistry. Our preliminary results suggest that it is possible to detect DNA using AlGaN/GaN HEMT sensor. However, further experiments will 1) assess if mismatched target DNA contribute to any change in current measured, and 2) evaluate the reproducibility and the accuracy of the device.

INTRODUCTION

The development of biosensors for detecting bacteria is an area of intense research due to the large number of instances of bacterial contamination. Several different methods including optical [1-3], changes in mass [4], electrochemical detection [5] have been developed for this purpose. Most of these methods include using a labeling agent [6-7] or are expensive, time consuming, tedious and destructive. Biosensors based on semiconductor based field effect transistors are better because they are label free, nondestructive and fast [8-11].

A field effect transistor (FET) is a very efficient device in converting a biological signal into an electrical signal due to its sensitivity to changes in the surface potential. AlGaN/GaN based high electron mobility transistors (HEMT) are ideally suited for such devices since they have a high electron sheet concentration induced by spontaneous and piezoelectric polarization of the strained AlGaN and the GaN layer [12-13]. Kang and others have demonstrated the successful detection of DNA using the AlGaN/GaN field effect transistor [14].

In this work, we propose detection of bacterial DNA based on the principle of DNA hybridization. DNA hybridization is the process by which the complementary sequences of two single-stranded DNA bind to form a double-stranded DNA [15]. Because the DNA molecules are charged, the hybridization of a two ssDNA molecules with matching complementary sequence will results in the charge density change on the surface where this hybridization has occurred. This change in the charge density will result in a change in the surface potential on the surface.

EXPERIMENT

The HEMT structure consists of a thin AlN layer, 2.7μm GaN buffer, 20nm AlGaN and a 2nm GaN cap layer. The HEMT wafer was purchased from SVTA. The GaN cap layer helps in reducing the surface states and in improving the ohmic source and drain contacts without having any ill effects on the schottky contact. The epilayers were grown on top of sapphire. The 2DEG mobility is greater than 1300cm^2/v-s at room temperature.

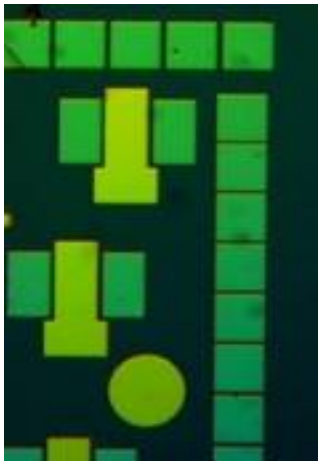

Figure 1: Picture of the device.

Ti/Al/Ni/Au were deposited and then annealed at 750°C for 30s under flowing N_2 gas which made the ohmic contacts. These processes were performed by the standard lithographic, sputtering and lift-off techniques. The Schottky contacts were made by sputtering Ni/Au [16-17]. The fabricated device structure is shown in Fig. 1. After making the gold wire bonding to the ohmic contacts polydimethylsiloxane (PDMS) was spin coated on the device. Using the same mask, which was used to pattern the gate, Mo/Ni metal layer were patterned on the PDMS, by the standard lithographic and lift-off techniques. The PDMS applied on the gate area was dry etched using NF_3 plasma.

The DNA immobilization for the purpose of detection was carried out using the following procedure: The gold coated gate surface was first cleaned with methanol and then with acetone to remove any grease residues present on the surface. It was then cleaned with a solution mixture containing H_2O_2 (30%), NH_3 (30%), milliQ H_2O in a 1:1:5 ratios for 10 min. The surface was then thoroughly washed with deionized water. Then the gate surface was treated with 50 µl of thiolated probes (1 µM) 5'-SH-$(CH_2)_6$-GGTGGTGCTAAGGCAATGATAG-3' in immobilization buffer for 4 h. The surface was washed with immobilization buffer and then treated with 50 µl of 1 mM MCH in Abs. ethanol for 90 min, before final washing with water. The I-V characteristics of the device were measured at regular intervals of 1 h.

Hybridization experiments were then carried out at 25°C by dropping 50 µl of the target ssDNA of concentration 1µM 5'-CTATCATTGCCTTAGCACCACC-3' in hybridization buffer for a total time of 15 min. The variation in current due to DNA hybridization was recorded (Fig 6). All experiments were carried out without displacing the HEMT from the analyzer, to avoid discrepancy in the readings recorded as the result of changes in the position.

RESULTS AND DISCUSSION

The I-V characteristics of the device were measured in the range where the detection is carried out (Fig. 2). Fig. 3 shows the gate current as a function of source-drain voltage with the same gate biasing used to measure the I-V characteristics. The gate current was also measured in the same range where the sensing was carried out.

In order to make the electrical measurements, we had to have a robust gold wire bonding to the ohmic contacts. For that Ti/Al were first deposited and then annealed at 750°C for 30s under flowing N_2 gas. This process was followed by depositing a thin layer of chromium followed by Ni/Au, which was the most robust gold wire bonding to the ohmic contacts (Table I). The experiments mentioned in Table I were carried out on a silicon wafer (Fig. 4).

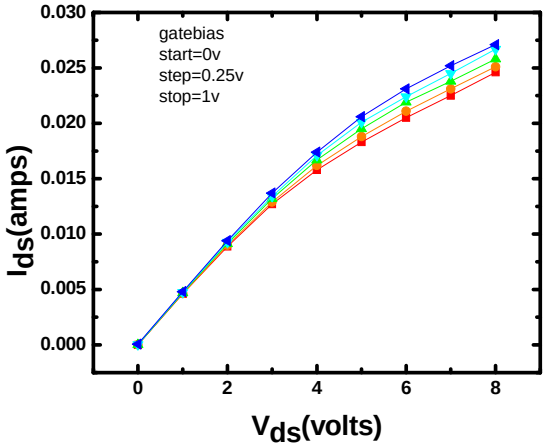

Figure 2: I-V characteristics of the HEMT in the range where the sensor device is used.

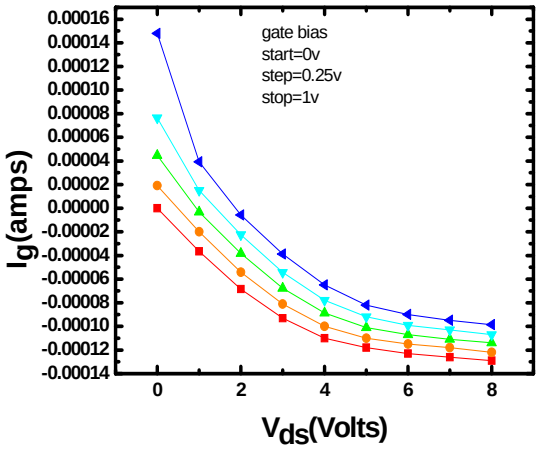

Figure 3: A graph showing the gate current as a function of the source-drain voltage.

A change in the I-V characteristics of the device was noted during the probe immobilization and when the target ssDNA was passed. The change in the I-V characteristics (Fig 5) when the probe DNA is immobilized was as expected because the thiolated probes take time to rearrange to form the monolayers.

TABLE I

Exp. No.	Order of depositing ohmic contacts	Annealing temperature	Adhesion characteristics
1	Ti/Al/Ni/Au	750 °C	Doesn't bond well
2	Ti/Al/Ni/Au	850°C	Doesn't bond well
3	Ti/Al +annealing+ Ni/Au	750°C	Doesn't bond well
4	Ti/Al +annealing+ Ni/Au	850°C	Doesn't bond well
5	Ti/Al/Ti/Au	750°C	Doesn't bond well
6	Ti/Al/Ti/Au	850°C	Doesn't bond well
7	Ti/Al +Annealing+ Ti/Au	750°C	Doesn't bond well
8	Ti/Al +Annealing+ Ti/Au	850°C	Doesn't bond well
9	Ti/Al +Annealing + Cr/Ni/Au	750°C	Bonds well

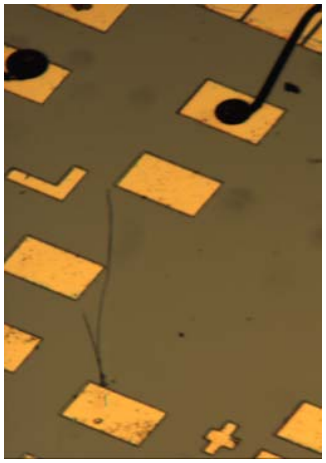

Figure 4: Gold wire bonded to the contact.

The change in current was not observed until 600sec after the target DNA was added. This change in current is sharp in the initial 300sec. This is expected since initially there are enough probe DNA for the target DNA to hybridize with.

Further experiments need to be carried out to check if there is any current contribution due to mismatched target DNA. A Pt reference electrode will also be used in future experiments to bias the gate. There is also a need to perform further trials to check for the reproducibility and the accuracy of the device.

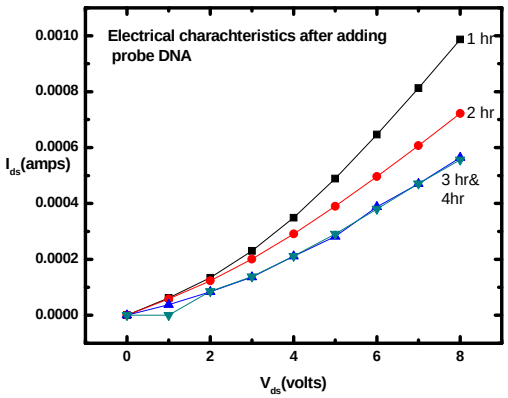

Figure 5: A graph showing I_{ds}- V_{ds} as a function of time after adding the probe DNA.

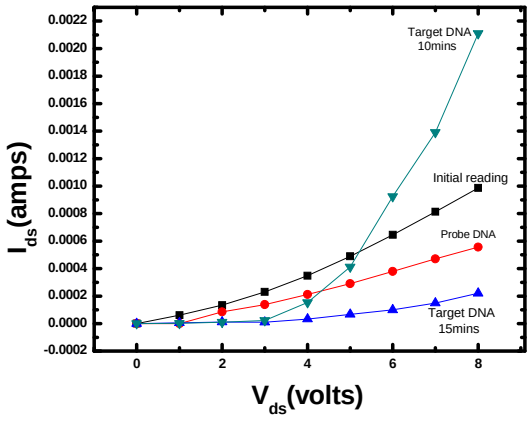

Figure 6: A graph showing I_{ds}- V_{ds} after the probe immobilization and after the target DNA is added.

SUMMARY

AlGaN/GaN based HEMT was fabricated with Ti/Al/Ni/Au ohmic contacts and Ni/Au schottky contacts for the purpose of biosensing. PDMS was used as an encapsulating agent for the source and drain ohmic contacts. The PDMS on the gate area of the device was dry etched using NF_3 plasma. The DNA immobilization on the Au gate is carried out using thiol based chemistry. Our preliminary results suggest that it is possible to detect DNA using AlGaN/GaN HEMT sensor. However, further experiments will 1) assess if mismatched target DNA contribute to any change in current measured, and 2) evaluate the reproducibility and the accuracy of the device.

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ACRONYMS

HEMT: High electron mobility transistor
PDMS: Polydimethylsiloxane
SAM: Self assembled monolayer