ABSTRACT

We first time demonstrate an electrolyte/semiconductor junction diode formed on single-crystal gallium oxide ($\beta$-Ga$_2$O$_3$) exhibiting Schottky-type behavior and its ability in single base mismatch detection of let 7a and let 7f miRNA at picomolar (pM) level. The diode has exhibited good electrical characteristics and its ideality factor[1], threshold potential and Schottky barrier height could be calculated from its I-V characteristics. A liquid junction diode has been demonstrated for multi biosensing application and 100 pM target miRNA (let 7a) could be detected from single base mismatch let 7f through the resistivity shift with high specificity.

KEYWORDS: $\beta$-Ga2O3, electrolyte/semiconductor junction, miRNA, liquid junction diode

INTRODUCTION

$\beta$-Ga$_2$O$_3$, a transparent conducting oxide (TCO) has advantages over other conventional TCOs owing to its unique important properties such as large band gap (4.9 eV), deep UV -transparency, good electrical conductivity in bulk form in addition to the common TCO properties such as visible light transmittance and chemical stability. Ueda et al. reported good conductivity of the bulk single-crystal $\beta$-Ga$_2$O$_3$ grown through floating zone method and possibility of controlling the conductivity[2]. The fabrication of Schottky barrier diode[3] using Ga$_2$O$_3$ single crystal substrate demonstrated relatively simple device structure and fabrication process, good ohmic behavior of the electrodes, and a reasonably high reverse breakdown voltage that can be associated with high crystal quality of the substrate. Reported single-crystal Ga$_2$O$_3$ based transistor [4] exhibiting excellent characteristics confirms its usability in future power devices.

The recent growing interest to develop novel, cheap and efficient integrated biosensing system has drawn attention to aqueous-based electronics systems [5] and an effort to the understanding of solid-liquid junctions can greatly help in future bio device development. Previous work [6] reported developing a nano fluidic diode based on a single nanopore analogous to that of a semiconductor diode and able to rectify ion currents. Here, we approached a rather simpler method of ion current rectification taking advantage of electrical characteristics of electrolyte/semiconductor junction and great potential of Ga$_2$O$_3$.

THEORY

When a semiconductor comes in contact with electrolytes, electrons diffuse from semiconductor into the electrolyte until the electrochemical potential of redox couple in solution, $E_{\text{Redox}}$ and of the electrons in the semiconductor is equilibrated. If n-type semiconductor is interfaced with an electrolytic solution, this transfer of charges would occur mostly from the semiconductor towards solution. The energy barrier in the junction determines the conductivity of this newly formed electrolyte/semiconductor. Such interface exhibits rectifying behavior which can be quite useful for the characterization of the semiconductor surface at the presence of different bio molecules functionalized on it.
FABRICATION AND CHARACTERIZATION

The diode has been formed by introducing an electrolyte layer on top of the n-type $\beta$-Ga$_2$O$_3$ substrate surrounded by cylindrical poly(dimethylsiloxane) (PDMS) made wall and an electrode in contact with the electrolyte helps in the electrical characterization (I-V) of the S-E diode. Fig.1. explains the construction of the single diode on the gallium oxide substrate with thickness of 600 $\mu$m and the total effective area of the semiconductor surrounded by the PDMS made wall inside the fabricated diode is approximately 0.07 cm$^2$. The substrate exhibits n-type conductivity due to unintentional doping and the effective donor concentration ($N_d-N_a$) is $2.2\times10^{18}$ cm$^{-3}$. The I-V measurement (Fig 2.) of the formed diode has been done in different ionic concentrations (150 mM and 1 mM) considering the importance of Debye length in bio sensing.

Figure 1: a. Liquid junction diode formed on top of single crystal n-type $\beta$-Ga$_2$O$_3$ with ohmic contact on the bottom of the substrate for connectivity. An Ag/AgCl electrode with a diameter of 0.9 mm and thickness of 4.4 $\mu$m formed on top of SiO$_2$ makes contact with the electrolyte phase as well as covers the top of the PDMS wall sealing the $\beta$-Ga$_2$O$_3$ based diode. b. Symbol representing the liquid junction diode.

Figure 2: a. The current-voltage (I-V) characteristics of liquid junction diode formed on the $\beta$-Ga$_2$O$_3$ substrate with ionic concentration of electrolytes $150\times10^{-3}$ M, b. Semi-log plot of the characteristics curve a. , c. The (I-V) characteristics of the diode with $1\times10^{-3}$ M concentration of electrolytes. d. the (I-V) of the diode in the reverse bias mode with different electrolyte concentration – $150\times10^{-3}$ M, and $1\times10^{-3}$ M.
EXPERIMENT AND RESULTS

Based on the characterization of the device, the liquid junction diode has been applied for biosensing and Fig. 3 demonstrates the application of the formed diode in detection of target miRNA (let7a) with very low concentration and a good selectivity (Fig.3c). A basic measurement setup for the device is available in Fig.3a that shows the diode acting similar to a solid state diode. The diode surface could completely be used for the functionalization (Fig.3d) with biomolecules maximizing the use of the substrate area (Fig.3b) as the ohmic contact could be formed on the other side of substrate. The contact electrode has been sealed around electrolyte ensuring the better control of parameters.

CONCLUSION

We report an easy-to-fabricate junction diode formed on a single crystal gallium oxide ($\beta$-Ga$_2$O$_3$) and have confirmed the operation of the device in low ionic concentration and various temperature before using it as a biosensor. We also have demonstrated an array of diode that can be used in resistivity-based biosensing and its ability in low concentration (100 pM) highly specific (single base mismatch) miRNA detection. The study shows that the gallium oxide based electrolyte diode and its electrical characterization can be vital for the development of future biosensing device.

REFERENCES


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