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Temperature dependence of the resistance of AlGaN/GaN heterostructures and their applications as temperature sensors

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1. Introduction

Temperature sensors are estimated to account for about 80% of world's sensor market [1]. Despite the plethora of sensors covering the range from cryogenic temperatures to thousands of degrees Kelvin, there is demand for alternative robust sensors to monitor temperatures in harsh environments such as outer space and nuclear power stations.

Two-dimensional electron gas (2DEG) heterostructures such as AlGaAs/GaAs and AlGaN/GaN are widely used for fabricating high performance transistors and related devices. Separation of conducting electrons from dopant atoms leads to remarkable differences in the electrical properties of 2DEG-heterostructires compared with bulk semiconductors. Moreover, the absence of dopants in the conduction path affects the temperature dependence of electron transport in the 2DEG and these unique characteristics could be exploited for temperature sensing.

The AlGaN/GaN system is of particular interest because of its physical stability and chemical inertness at elevated temperatures, as well as its radiation hardness due to its wide band gap.

Extensive research has produced a deeper understanding of the electrical properties of 2DEG in AlGaN/GaN systems. However, most reports on the transport of 2DEG electrons at low or ambient temperatures, and our knowledge of the behavior of 2DEG electron transport in AlGaN/GaN heterostructures at high temperatures is still limited.

Here, we describe the temperature dependence of the resistance of 2DEG-AlGaN/GaN structures in the temperature range 3 K to 1000 K. We found that this system behaves as a high performance temperature sensor and were able to express our experimental results in terms of a well defined resistance-temperature (R-T) relationship.

2. Experimental

The AlGaN/GaN-2DEG heterostructures were grown by MOCVD on sapphire substrates. Fig. 1 illustrates the three structures, where the location of the 2DEG is highlighted by the thick black lines. The Al content and thicknesses of the AlGaN layers were varied to control the electron density and mobility of the 2DEGs. Ohmic electrodes

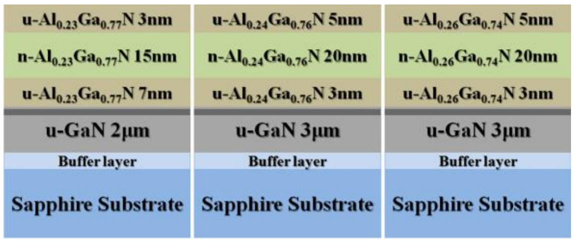

Fig.1. Illustrations of the different AlGaN/GaN heterostructures designated from the left to the right as 'd', 'e' and 'f'.

were formed using metallic multilayers: Ti (50 nm)/Al (200 nm)/Ni (50 nm)/Au (100 nm). High temperature rapid thermal annealing at 1123K for 30s was used to form the ohmic contacts. Finally, the desired shapes and dimensions of the samples were cut by dicing from the epitaxial wafers. The resistance of the heterostructures was measured by 2-electrode and 4-electrode configurations from 3K to 1000 K. The mobility and electron density of the 2DEG channels was measured using the van de Pauw method. Calibrated K-type and T-type thermocouples were used for reference measurements during high and low temperature measurement, respectively.

2. Results and Discussion

Fig. 2 (a) shows the resistance-temperature relationship of bar-shaped samples with the same "d" structure, where the numerals in the legend refer to the sample widths. The lengths of the bars were constant at 3mm. The same monotonic trend was observed for all samples, with the resistance increasing with temperature up to 1000 K, and remaining almost unchanged below 77 K. This behavior indicated metallic conduction associated with two-dimensional electron gas structures. These electrical characteristics are especially useful for temperature sensing, since changes in the magnitude of the resistance were regular and stable. Moreover, depending on the aspect ratio of samples, a series of well defined resistances were obtained at a given temperature, (Fig. 2 (a)). Fig. 2(b) shows the effect of the configuration of heterostructures on the re-

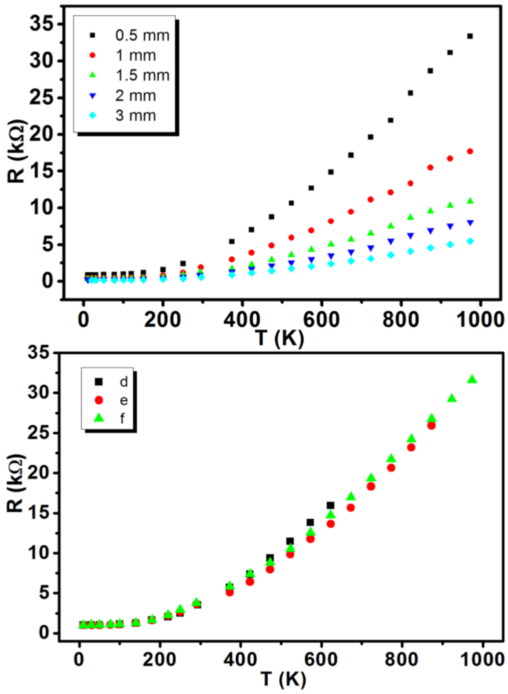

Figure 2. Resistance-Temperature (R-T) curves obtained for samples with different aspect ratios (a) and heterostructure designs (b).

sistance-temperature measurements for rectangular shaped samples. The R-T characteristics were not sensitive to changes in Al content or spacer layer thickness. Thus tuning the Al content or spacer layer thickness over small range does not affect the temperature sensitivity. On the other hand, these results imply that a slight fluctuation in these parameters will not affect device performance, which is desirable for real application and large scale manufacture of sensors.

The temperature dependence of the resistance at high temperatures was nearly linear, and these results could be

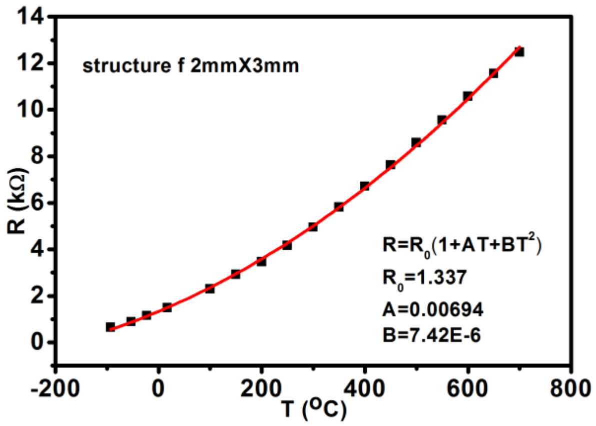

Fig.3. Example of fitting the measured R-T results for sample “f” above 180K to the Callender-Van Dusen equation.

expressed well by a function containing T and T^2 term,

$$R=R_0(1+AT+BT^2),$$

where, R_0 is the resistance at 0 °C, A and B are parameters, and T is temperature in Celsius. Fig. 3 shows the fitting results using this function for the “f” structure.

This relationship is known as the Callender Van-Dusen equation, and is used for analyzing resistance temperature detectors (RTD) made of platinum above 0 °C.

Our results showed that near room temperature, the sensitivity of our sensors was about two times larger than conventional RTD sensors. Moreover, at 600°C the performance of our sensors was five times better than RTDs.

Notably, AlGaN/GaN 2DEG sensors were more sensitive than conventional sensors over a wide range of temperatures, and the advantages of the nitride sensors, such as radiation hardness, structural compactness and the simple temperature-output relationship, makes them suitable for special applications such as in space and in nuclear power plants.

3. Conclusions

In summary, we described the electrical characteristics of novel semiconductor-based temperature sensors fabricated using AlGaN/GaN two-dimensional electron gas heterostructures. They showed monotonic resistance changes from 3K to 1000K. The R-T curves above 180K were fitted using a single Callender-Van Dusen equation, which is generally used for Pt-type RTD sensors. More work is needed to further increase the sensitivity of these type of sensors, however, their performance is already sufficient for niche applications..

4. Acknowledgements

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