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Schottky behavior of reduced graphene oxide at various operating temperatures

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A B S T R A C T

Demand of portability has been a growing trend due to the thirst of catching up with the latest evolution of technology. This scenario has urged power supply designers to develop devices that are relatively smaller, faster and having a higher percentage of efficiency. In contrast, smaller devices tend to experience overwhelming heat dissipation which can be hazardous to the devices. A Schottky diode is a semiconductor diode which has a relatively low forward voltage drop and fast switching action. Despite having low voltage drop, Schottky devices are extremely sensitive to elevated temperature owing to high leakage at reverse bias region. The leakages are due to low energy barrier which is susceptible to thermal runaway when a nominal amount of heat is applied. This paper presents the study of Schottky behaviour of reduced graphene oxide (RGO) at various operating temperature. RGO has superior electronic and thermal properties as well as high carrier mobility. Graphene was obtained by chemical exfoliation of graphene oxide, which is a reduction method. Through spray-coating, the RGO is deposited onto a trench-structured Schottky base to form a Schottky diode. Electrical characterization has been carried out at different range of temperature; ranging from 25 °C to 125 °C. Result shows that overall, the device has the same range voltage drop around 1 V in all five different temperatures and is also considered to have a significantly low leakage current. Furthermore it also shows a unique current-voltage (I-V) pattern in which the impedance tangent increases from 25 °C to 50 °C but as the temperature gets higher, the impedance approaches the characteristics of a room temperature.

1. Introduction

Schottky diode is one of the simplest forms of device which has a relatively low voltage drop and fast switching action. This makes it ideal for output stages of switching power supplies, which has significant uses in high frequency applications including low power signal devices and switching diode time requirements of less than 100 picoseconds [1]. A further advantage of a Schottky structure is that it can be fabricated using relatively low temperature techniques, which does not generally need high temperatures for impurity diffusion [2]. The Schottky structure is widely used in the electronics industry and its applications are still valid for use until today but only limited to certain operations. One of the problems associated with Schottky devices is related to their metal electrodes. Breakdown has been noticed around the edge of the metallized area at high temperatures [3,4]. This arises from the presence of high electric fields around the edge of the plate, which results in relatively low reverse voltage tolerance and high reverse leakage current. These limitations are related to the Schottky barrier determined by the metal work function of the metal electrode, the band gap of the semiconductor, and the type and concentration of dopants in the semiconductor layer [5].

To further improve the effect of the limitation, introduction of a new material is a risky, yet great way to start. Thus, replacing the conventional metal layer of the Schottky diodes with a nanostructured carbon film shows promising outcomes [6]. Nanostructured carbon has amazing characteristics such as superior electronic and thermal properties as well as high carrier mobility. The nanoscale carbon materials consist mainly of graphite, the standard form of

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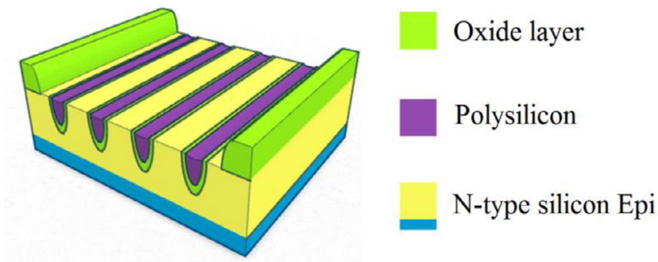

Fig. 1. Cross-sectional diagram of trench-structured Schottky.

carbon. In literal definition, graphite means an allotropic form of the element carbon consisting of layers of hexagonally arranged carbon atoms in a planar condensed ring system [7].

Graphene, which is known to be a 'single, one-atom thick, sheet of graphite' is gaining a lot of attention for its unique and outstanding characteristics [8]. The breakthrough of graphene for having extreme mechanical strength and high electronic mobility of $\sim 2 \times 10^5$ cm^2 V^{-1} s^{-1} with low resistivity of $\sim 10^{-6}$ Ω.cm [9,10] as well as exhibiting extremely high intrinsic thermal conductivity [8] has attracted huge interest amongst the researchers. Graphene and its compounds are increasingly used in fabricating transistors that exhibit extremely superior performance [11–13].

It has been proven that graphene is a potential material to be incorporated with present-day transistors and diodes for its proper quality conduction comparative to that of metals. The room temperature thermal conductivity of graphene ranges from 3080 – 5300 W/mK [14,15]. This quality is exactly what the industries are seeking for; both in the advancement of technology and its potential benefits towards the environment [16]. To obtain graphene in its natural state is extremely difficult, thus researches are more focused on obtaining it by the reduction of graphene oxide thin films by both chemical and electrochemical methods from the dissolving of graphite powder [17–20]. Reduction of graphene oxide produces graphene-like structures and it could be an environmentally friendly way for large-scale production of one to several layer graphitic thin films [21]. It is also considered to be the most promising way, among other methods [22], to mass produce graphene based devices to be incorporated into the industry with minimal cost.

The trend to make everything faster, smaller and portable urges power supply designers to produce smaller device packaging, thus making it work relatively faster. However, there is a much larger concern to be looked into; smaller packaging means higher chance for heat dissipation [23]. This can be not only hazardous, but also one of the main contributor to the production of high leakage current.

To overcome the problem, high heat flux management is one of the ways to remove heat from localized hot spots and reduced graphene oxide (RGO) is believed to be a material that can be incorporated into chips for this solution [16]. RGO has been demonstrated to be a promising heat spreader material for heat dissipation of hot spots with high heat flux for thermal management of local hot spots in electronic devices [10,20,24].

The present work relates to a Schottky diode and a method for manufacturing the Schottky diode, and more particularly to a method for manufacturing a trench Schottky diode having characteristics of lower reverse leakage current, lower forward voltage drop, higher reverse voltage and less reverse recovery time. For improving the Schottky diode device performance, a trench type Schottky diode has been proposed, [25] in which a thermal oxide layer is grown in trenches, and then a polysilicon is filled in trenches of the device to pinch off the reverse leakage current, so as to reduce the current leakage of the device. The trench structure of Schottky diode can be seen in Fig. 1.

In this paper, we demonstrate how RGO is implemented into the construction of Schottky diode and the effect it brings to the Schottky behavior in various temperature operating ranges. By combining both advantages of using trench Schottky as the structure and RGO as a material, it is believed that the device will have outstanding electronic characteristics and can overcome the problems caused by high temperature operation. This was proven when the electrical characterization of the sample was tested. The current-voltage (I-V) test of the sample showed very promising results, as it presented very low leakage current as well as low turn-on voltage.

2. Experimental procedure

2.1. Fabrication & deposition of reduced graphene oxide (RGO)

By using graphite powder [C, Aldrich, 99%], the RGO was synthetized *via* modified Hummer's method [26,27] in producing graphene oxide (GO) solution. Sodium nitrate [$NaNO_3$, Aldrich, 99%] and concentrated sulphuric acid (H_2SO_4) which acts as a solvent were mixed and stirred at a constant speed. Then, potassium permanganate [$KMnO_4$, Aldrich, 99%] and distilled water were gradually added for dilution [19] which caused the formation of diamanganese heptoxide (Mn_2O_7). It is an active species that has the ability to selectively oxidize unsaturated double bonds. This adds a great significance during oxidation in its graphitic structure and reaction pathways [28]. To form agglomeration of graphene nanosheets, aqueous ammonia ($NH_3.H_2O$) and hydrazine hydrate was added. The RGO thin film was deposited on the trench-structured substrate by pressurized spray coating method in which the amount of spray volume controls the film thickness [29].

The condition of RGO depends on the state of temperature reaction [25]. In low temperature reaction, the edge of graphite was oxidized and intercalated with the aid of an oxidizing agent. Hydroxide [OH] was formed during this process. In mid temperature reaction, the oxidation ability was improved furthermore. More oxygen functional groups are formed in this process and the oxidizing agent penetrates into the internal graphite layers. This

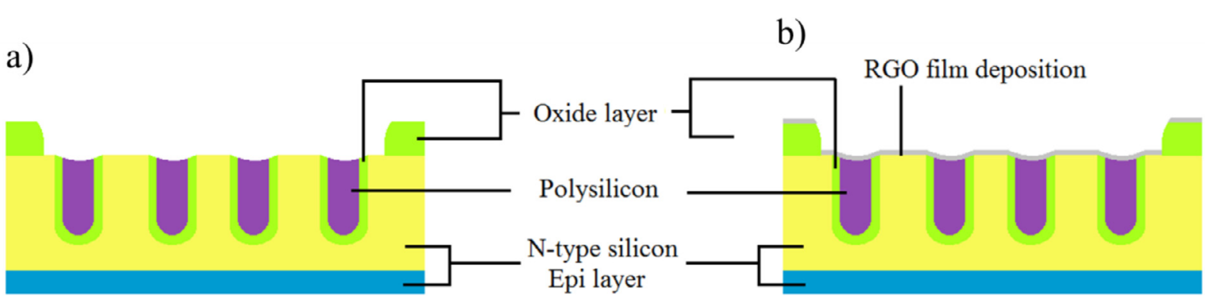

Fig. 2. Cross-sectional diagram of trench-structured Schottky substrate (a) before, and (b) after RGO deposition.

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