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Temperature dependent current–voltage characteristics of Au/n-type Ge Schottky barrier diodes with graphene interlayer

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ABSTRACT

Current–voltage (*I–V*) characteristics of Au/n-type Ge Schottky barrier diodes (SBDs) with and without graphene interlayer were investigated in the temperature range of 180–340 K. For both devices, the Schottky parameters –such as the barrier height and ideality factor–showed strong temperature dependence, indicating a deviation of the *I–V* characteristics from what the thermionic emission (TE) mechanism predicts. On the basis of the TE theory along with the assumption that the barrier height takes on a Gaussian distribution, the temperature dependence of the *I–V* characteristics of the Au/n-type Ge SBDs with and without graphene interlayer was explained in terms of Schottky barrier inhomogeneity. Experimental results reveal the existence of a double Gaussian distribution of barrier height in the Au/n-type Ge SBD, whereas only a single Gaussian distribution of barrier height existed in the Au/graphene/n-type Ge SBD. Furthermore, the degree of barrier inhomogeneity of the Au/graphene/n-type Ge SBD is lower than that of the Au/n-type Ge SBD. The superiority of the Schottky barrier for the Au/graphene/n-type Ge SBD could be associated with the passivation of the Ge surface by the graphene interlayer.

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1. Introduction

Graphene has become a valuable material in fundamental science and technology because of its excellent electronic, optical, thermal and mechanical properties [1–4]. The prominent features of graphene have facilitated its application in high-performance devices, including field effect transistors [5], photodetectors [6], light emitting diodes [7], chemical sensors [8] and supercapacitors [9]. For instance, Mayorov et al. [10] reported that high room-temperature mobilities in graphene exceed 100.000 cm^2/V s and over a 1 μm distance ballistic transport. Furthermore, Li et al. [11] demonstrated that graphene can be used not only as a transparent, conductive electrode for light transmission, but also as an active layer for electron/hole separation and hole transport, as well as an antireflection layer in graphene–Si solar cells. Zeng et al. [12] fabricated high-speed photodetectors based on photocurrents generated at the graphene-semiconductor Schottky interface, in which graphene was used as a transparent electrode. Additionally, Schedin et al. [8] demonstrated that graphene is an ideal material for the high-sensitivity gas detection and confirmed that their fabricated sensor had detection limits on the order of one part per billion, the same as that of other existing gas detectors.

Recently, germanium (Ge) has been considered to be a promising channel material for next-generation, high-mobility complementary metal-oxide-semiconductor (CMOS) devices in terms of overcoming the scaling limits of its Si counterpart. A major challenge in the realization of high-performance Ge-based CMOS devices is posed by the effect of strong Fermi-level pinning close to the valence band of Ge [13–16]. This makes it difficult to modulate the barrier heights of metal-Ge junctions via the selection of metals

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with different work functions. Some techniques for controlling the barrier height of metal-Ge contacts have been proposed, such as plasma treatment [13], sulfur segregation [14] and the insertion of a thin insulator layer between the metal and Ge [15,16]. Most recently, we investigated the effect of a graphene interlayer on the electrical properties of Au/n-type Ge Schottky barrier diodes (SBDs) using current–voltage (*I*–*V*) and capacitance–voltage (*C*–*V*) characteristics, and demonstrated that the minimizing the Fermi-level pinning of Ge could be associated with the passivation of Ge surface by graphene [17].

However, despite the prominent features of Au/n-type Ge SBDs with graphene interlayer, detailed information about the Schottky interface –such as temperature dependence of the Schottky barrier parameters–still remains unclear, though this is required for the further enhancement of device performance. As a continuation of our previous work, here we investigated the nature of the Schottky interface of the of Au/graphene/n-type Ge SBD, and directly compare it with that of the Au/n-type Ge SBD in terms of temperature-dependent *I*–*V* characteristics. The non-ideal *I*–*V* behavior of Au/n-type Ge SBDs with and without graphene interlayer is explained in terms of barrier inhomogeneity assuming that the barrier height takes on a Gaussian distribution. It will be shown that single and double Gaussian distribution of barrier height exist in Au/n-type Ge SBDs with and without graphene interlayer, respectively. It is further shown that, owing to the passivation of the Ge surface by the graphene interlayer, Au/graphene/n-type Ge SBD exhibits more homogeneous Schottky interface than Au/n-type Ge SBD.

2. Experimental details

Large-area, single-layer graphene sheets were grown by chemical vapor deposition (CVD) on high quality polycrystalline copper (Cu) foils (25 μm thick) using a process described elsewhere [18]. A 500 nm-thick PMMA (Micro Chem, 950 PMMA C4) was spin-coated onto the graphene film grown on Cu foil at 3000 rpm for 30 s. Then, the unwanted graphene was removed from the back side of the Cu foils by O_2 plasma process. The Cu was then etched from the PMMA-supported films using a 0.05 mg/L solution of ferric nitride [$Fe(NO_3)_3$], yielding PMMA/graphene sheets. Finally, the PMMA/graphene sheets were washed several times in deionized water and isopropyl alcohol.

Fig. 1 shows schematic diagrams of the fabrication process of the Au/n-type Ge SBD with a graphene interlayer. An n-type (100) Ge wafer with a carrier concentration of 1×10^{16} cm^{-3} was used as the basic substrate. The Ge wafers were initially degreased with organic solvents like acetone and methanol by means of ultrasonic agitation for duration of 5 min in each step to remove contaminants, followed by rinsing in deionized (DI) water and then drying in N_2 flow. The wafers were then etched with a buffered oxide etch (BOE) for 60 s to remove native oxide from the substrate. After the cleaning process, the PMMA/graphene sheet was transferred onto the Ge substrate, followed by the removal of the PMMA film using acetone for 12 h (Fig. 1(a)). The 2D-to-G intensity ratio, calculated from the Raman spectrum taken from graphene transferred onto the Ge substrate, was found to be >2, corresponding to the typical monolayer feature of CVD-grown graphene [19]. Afterward, a circular Au (100 nm) electrode with a diameter of 1 mm was deposited on the graphene through a metal shadow mask by electron-beam evaporator at a pressure of ~3.8×10^{-6} Torr (Fig. 1(b)). At this stage, redundant graphene was removed by reactive-ion etching (RIE) with a power of 30 W, resulting in the formation of a circularly shaped mesa structure, as shown in Fig. 1(c). Finally, in order to form the bottom electrode, a Ga–In eutectic alloy was covered onto the back side surface of Ge substrate (Fig. 1(d)). For a comparison, the intimate Au/n-type Ge SBD without graphene interlayer was fabricated on the n-type Ge substrate under similar process conditions. Namely, after surface cleaning and subsequent removal of native oxide from Ge substrate, the sample was inserted into the deposition chamber of electron-beam evaporator immediately in order to form the circular Au electrode through metal shadow mask. Then, for the formation of the Ohmic contact, metallization using Ga–In eutectic alloy was performed on the back surface of the Ge substrate without RIE process. The *I*–*V* measurements of Au/n-type Ge SBDs with and without graphene were performed using a semiconductor parameter analyzer (Agilent 4155C) over the temperature range of 180–340 K in steps of 20 K under dark conditions.

3. Results and discussion

Fig. 2 shows the forward and reverse bias semi-logarithmic *I*–*V* characteristics of the Au/n-type Ge SBDs with and without the graphene interlayer over the temperature range of 180–340 K in

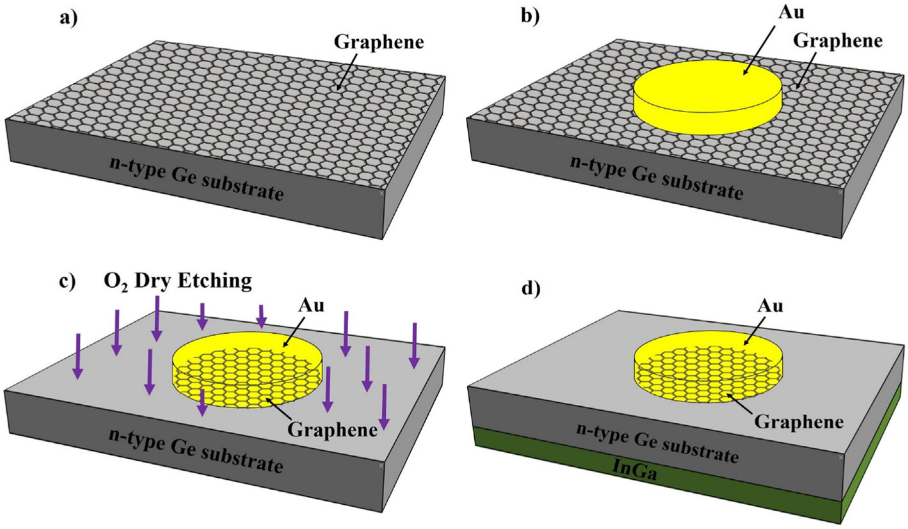

Fig. 1. Schematic diagrams illustrating the procedures for the fabrication of Au/n-type Ge SBD with a graphene interlayer: (a) Graphene transferred onto the Ge substrate, (b) Formation of the circular Au electrode, (c) Removal of redundant graphene using RIE process, and (d) Deposition of Ga–In eutectic alloy as the bottom electrode.

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