Superlattices and Microstructures 91 (2016) 306–312

Contents lists available at ScienceDirect

Superlattices and Microstructures

journal homepage: www.elsevier.com/locate/superlattices

Schottky barrier parameters and low frequency noise characteristics of graphene-germanium Schottky barrier diode

Zagarzusem Khurelbaatar [a, b], Yeon-Ho Kil [a], Kyu-Hwan Shim [a], Hyunjin Cho [c], Myung-Jong Kim [c], Sung-Nam Lee [d], Jae-chan Jeong [e], Hyobong Hong [e], Chel-Jong Choi [a, *]

[a] School of Semiconductor and Chemical Engineering, Semiconductor Physics Research Center, Chonbuk National University, Jeonju 561-756, Republic of Korea

[b] School of Information and Communication Technology, Mongolian University of Science and Technology, Ulaanbaatar 51-29, Mongolia

[c] Soft Innovative Materials Research Center, Institute of Advanced Composite Materials, Korea Institute of Science and Technology Wanju-gun 561-905, Republic of Korea

[d] Department of Nano-Optical Engineering, Korea Polytechnic University, Siheung 429-793, Republic of Korea

[e] Electronics & Telecommunication Research Institute, Daejeon 305-700, Republic of Korea

ARTICLE INFO

Article history:
Received 1 December 2015
Received in revised form 21 January 2016
Accepted 22 January 2016
Available online 27 January 2016

Keywords:
Graphene
1/f noise
Schottky contact
Ge
Current noise power spectral density

ABSTRACT

We investigated the electrical properties of chemical vapor deposition-grown monolayer graphene/n-type germanium (Ge) Schottky barrier diodes (SBD) using current–voltage (*I*–*V*) characteristics and low frequency noise measurements. The Schottky barrier parameters of graphene/n-type Ge SBDs, such as Schottky barrier height (Φ_B), ideality factor (n), and series resistance (R_s), were extracted using the forward *I*–*V* and Cheung's methods. The Φ_B and n extracted from the forward ln(*I*)–*V* plot were found to be 0.63 eV and 1.78, respectively. In contrast, from Cheung method, the Φ_B and n were calculated to be 0.53 eV and 1.76, respectively. Such a discrepancy between the values of Φ_B calculated from the forward *I*–*V* and Cheung's methods indicated a deviation from the ideal thermionic emission of graphene/n-type Ge SBD associated with the voltage drop across graphene. The low frequency noise measurements performed at the frequencies in the range of 10 Hz –1 kHz showed that the graphene/n-type Ge SBD had $1/f^{\gamma}$ frequency dependence, with γ ranging from 1.09 to 1.12, regardless of applied forward biases. Similar to forward-biased SBDs operating in the thermionic emission mode, the current noise power spectral density of graphene/n-type Ge SBD was linearly proportional to the forward current.

1. Introduction

Low-frequency electronic noise was first discovered in vacuum tubes, and was subsequently found in a variety of electronic devices and systems [1–3]. The main components of this type of noise are thermal noise, shot noise, flicker noise (also known as 1/f noise), and generation-recombination (G-R) noise. Thermal and shot noises are frequency independent and are

* Corresponding author.
E-mail address: cjchoi@jbnu.ac.kr (C.-J. Choi).

http://dx.doi.org/10.1016/j.spmi.2016.01.029
0749-6036/

related to a device's resistance and current. In contrast, 1/f noise and G-R noise are important at low frequencies and dominate at room temperature under bias [4]. Studies of 1/f noise are effective tools to measure the bulk as well as surface quality of semiconductors, and 1/f noise has been a compelling research topic for more than eight decades. In particular, the Schottky barrier structure provides a unique testing tool for 1/f noise measurement, since the band bending at the metal-semiconductor interface exposes the energetic and spatial distribution of the defects located at the Fermi level that are contributing most to the noise generation.

In recent years, graphene has attracted a lot of attention owing to its unique band structure, high electronic mobility, high mechanical/chemical stability, and ultra-thin dimensionality [5]. Meanwhile, germanium (Ge) has been considered as a promising channel material for next generation high mobility complementary metal-oxide-semiconductor devices in terms of overcoming the scaling limits of its silicon (Si) counterpart [6]. When considering the prominent features of graphene and Ge, the implementation of graphene into Ge, which confers higher carrier mobility as compared to Si, may enable many new device applications for post-Si technology [7]. Generally, a graphene contact to the semiconductor substrates with light doping (0.1–10 Ω cm) is described as a Schottky contact, which can be utilized in high performance optoelectronic and photovoltaic devices [8–10]. As devices are miniaturized into the nanometer-scale regime nowadays, $1/f$ noise studies become even more important, because this noise can be a limiting factor in the performance and application of nanoscale devices. Until now, studies on the 1/f noise in graphene-based devices were mainly focused on field effect transistor structures [11–14]. For instance, it was reported that l/f noise originated from the fluctuations in the number of charge carriers in the graphene channel associated with the trapping/detrapping of carriers in the substrate and/or with fluctuations in the mobility carriers [12,13]. Despite the technological importance of graphene/semiconductor Schottky barrier diode (SBDs), however, investigations of the $1/f$ noise associated with current transport through a graphene/semiconductor Schottky barrier are quite scarce. In this work, we have investigated Schottky barrier parameters and $1/f$ noise properties under various forward biases of graphene/n-type Ge SBDs, where the graphene acts as the metal and Ge as the semiconductor. We will demonstrate that the non-ideal I–V behavior of graphene/n-type Ge could be associated with the presence of high resistance. We will also show that the current noise power spectral density of graphene/n-type Ge SBDs exhibits $1/f^{\gamma}$ frequency dependence, with γ being close to unit, and is linearly proportional to the forward current.

2. Experimental methods

The graphene used in this study was grown on copper (Cu) foils (Nippon Mining, 0.035 mm) by the chemical vapor deposition (CVD) method. After each sample was loaded into a vacuum tube, the sample was heated up to 1050 °C and maintained at that temperature for 45 min for the hydrogen (H_2) annealing that leads to the reduction of the oxidized surface and large copper grains. The H_2 annealing was performed with an H_2 pressure of 67 mtorr and flow rate of 5 sccm. After the annealing process, graphene was grown under ~200 mtorr for 13 min with a gas flow of 20 sccm of methane (CH_4) in conjunction with 5 sccm of H_2. Finally, the graphene grown on the Cu foils was cooled down rapidly to room temperature with the same flow rate of H_2 in the absence of CH_4.

For the fabrication of graphene/Ge SBDs, an n-type Ge (100) substrate with a resistivity of 4.9–5.9 Ω cm was used as a starting material. After the surface was cleaned using acetone and isopropanol, 300-nm-thick SiO_2 layers were deposited on the substrate using plasma enhanced chemical vapor deposition. After that, the photoresist mask was patterned on SiO_2 to define graphene/Ge Schottky contact region with the area of 0.00785 cm^2 using standard photolithography process, followed by the formation of circular shaped open area of SiO_2 etched via reactive ion etching (RIE) process using a tetrafluoromethane (CF_4) precursor. For the graphene transfer onto the substrate, the graphene/Cu was coated with polymethyl methacrylate (PMMA) at 4200 rpm for 50 s. Subsequently, the Cu foil was etched away in ammonium persulfate [$(NH_4)_2S_2O_8$] solution, and then the PMMA-backed graphene was transferred onto the prepared substrate. The PMMA-backed graphene films on the Ge substrate were dried naturally and annealed at 180 °C for 30 min in a forced convection oven. The PMMA backing layer was dissolved away in warm acetone (60 °C) for 12 h, followed by rinsing thoroughly with isopropyl alcohol (IPA) and drying them with N_2 gas. The Raman spectrum (Fig. 1) taken from the transferred graphene on the n-type Ge substrate as measured by a laser with a wavelength of 490 nm indicated the typical monolayer feature of CVD-grown graphene, *i.e.*, a 2D-to-G peak intensity ratio of >2 [15]. Moreover, scanning electron microscope (SEM) examination (not shown here) revealed that the transferred graphene was continuously formed even over SiO_2 pattern, implying Ge surface was fully covered by graphene. Finally, to form the contact electrode, 10-nm-thick Ti and 100-nm-thick Au films were sequentially deposited and patterned on the graphene areas lying on SiO_2 using the lift-off process, as shown in the schematic and optical image (insets of Fig. 1).

The DC characterization of the graphene/Ge contacts was performed using a semiconductor parameter analyzer (Agilent 4155A) at room temperature under dark conditions. The measurement set-up for low frequency noise is shown in Fig. 2. The low-frequency current noise spectral densities at various forward biases were measured using a battery-powered low noise current amplifier (Stanford Research 570) at room temperature within a shielded room in order to minimize AC power source frequency coupling. An external multi-meter was used to verify the biasing voltage applied to the graphene/n-type Ge SBD. For each biasing point, the gain was adjusted to ensure that the output fell within the suitable detection range of the dynamic signal analyzer (Agilent 35670A).