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Graphene-Base Hot Electron Transistor with Schottky Emitter Junction Fabricated by Semiconductor Membrane Transfer

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Abstract

To improve the high-frequency properties of the bipolar junction transistor, the metal-base transistor was once proposed as the best candidate which however encountered both material and fabrication issues. As a semimetal, graphene is recognized as the best base material since the nature of ultra-thin thickness and high mobility. In this paper, a silicon-graphene-silicon transistor is fabricated by semiconductor membrane transfer, which is a graphene-base hot electron transistor with a Schottky emitter junction. It is expected as one of the most promising devices for ultra-high frequency operation which fully utilizes the supreme nature of graphene and the high efficiency of the Schottky emitter junction.

1. Introduction

The bipolar junction transistor is one of the most important devices ever invented. To make it faster, metal was once proposed to replace the semiconductor base which gave the metal-base transistor. It is the best candidate in theory for high frequency operation because of a negligible base transit time of the hot electron and a small emitter junction charging time of the Schottky junction emission [1]-[3]. Although the thinner the metal the larger the base transmission coefficient, when metal goes too thin, the quality of the metal can be hardly maintained and the base resistance inevitably increases. The metal-base transistor can either be hardly fabricated since a general fabrication method is still missing. Graphene is an ultra-thin semi-metal with ultra-high in-plane mobility which is naturally recognized as an ideal base material. A graphene-base hot electron transistor with a Schottky emitter junction is shown in Fig. 1. Simulation works showed even terahertz operation was possible [4]. The feasibility to employ graphene as a base material was also verified by the counterpart devices which emitted carriers via tunneling through oxide layers [5]-[7]. In this study, a silicon-graphene-silicon (Si-Gr-Si) transistor is fabricated and analyzed. With further engineering, ultra-high frequency operation is expected for the proposed transistor which combines the advantages of the hot electron transit, the outstanding nature of graphene and the Schottky junction emission.

2. Experiments

As shown in Fig. 2, the fabrication flow for a Si-Gr-Si transistor started from patterning of an n-type Si substrate with a SiO_2 capping layer via concentrated HF, leaving a window to the Si substrate (referred as the bottom Si). Graphene and Si transfer were then performed one after another. The graphene was grown by CVD on Pt and transferred by the bubbling method [8]. O_2 annealing was performed to clean the residue of a polymer of PMMA. An silicon-on-insulator (SOI) substrate with an n-type top Si layer was employed as a Si membrane provider. The top Si layer was patterned into a square via reactive-ion etching (RIE). Concentrated HF was used to etch away the underneath SiO_2. Polydimethylsiloxane (PDMS) was employed to transfer the square Si membrane (referred as the top Si) onto the Gr-bottom Si substrate [9]. Isolation and metallization were performed sequentially. Optical and SEM images of the fabricated Si-Gr-Si transistor were shown in Fig. 3.

3. Results and Discussions

The Ohmic contact characteristics between graphene and the probe, as well as the top Si and the probe were shown in Fig. 4. In the RIE process, the etching of Si surface began after the complete etching of the above photoresist. The sufficient RIE process not only gave a patterned Si but also gave an Ohmic contact between the top Si and the probe due to the generation current. For a typical Si-Gr-Si transistor, the Schottky characteristics of the top Si-Gr and the Gr-bottom Si junctions were shown in Fig. 5 (a). For the top Si-Gr junction an on-to-off current ratio of 6.6×10^4 at ±2 V was achieved. The on-current at -5 V was as high as 32.3 A/cm^2 which was more than 7-orders-of-magnitude higher than the Si-SiO_2-Gr tunnel junction [6]. The high current of the Schottky junction emission is highly needed in the high frequency applications. Next the characteristics of a typical Si-Gr-Si transistor biased in the common-base mode were shown in Fig. 5 (b) where the top Si was used as the emitter. The input characteristics I_e-V_e were almost the same as the diode behavior of the top Si-Gr junction without obvious affection by V_c, indicating that the emitter and the collector was not in contact. The transfer characteristics I_c-V_e were also shown and a clear dependence on V_e of I_c indicated that at the collector a successful collection of the emitted electrons from the emitter was achieved. When V_e=0 and V_c>0, a large I_c was observed which was the leakage current of the collector junction. In the calculation of the current gain, this leakage was ruled out. When V_c=0, the leakage was negligible, the current I_c was formed directly by the collected electrons from the emitter. The calculated common base current gain was shown in Fig. 5 (c). The current gain was above 10% at biases of V_e=-5 V and V_c=4 V. The current gain increased with increased biases V_c and V_e, which can be understood from the graphene-quantum-capacitance point of view. As shown in Fig. 6, the increased biases resulted an increased electrical field at the collector junction and the tunnel distance of an electron decreased. Previously those scattered electrons which could not across the collector junction barrier can now tunneled the barrier which increased the current gain. The same model could also be used to explain the non-saturation in the output characteristics as shown in Fig. 5(b). For the proposed transistor, the current gain and the output characteristics can be further improved through material engineering such as using a germanium collector which is currently under development.

4. Conclusions

A Si-Gr-Si hot electron transistor was fabricated by semiconductor membrane transfer. Schottky junction emission induced a much larger current compared with the tunnel junction emission for a better performance in the high frequency applications. With proper material combinations, high performance devices for ultra-high frequency applications are expected since the minimized emitter charging time, base transit time and base resistance of the proposed transistor.

Acknowledgements

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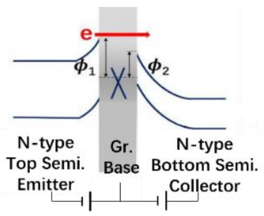

Fig. 1 An illustration of a graphene-base hot electron transistor with a Schottky junction emitter in the on-state. Semiconductors are n-type.

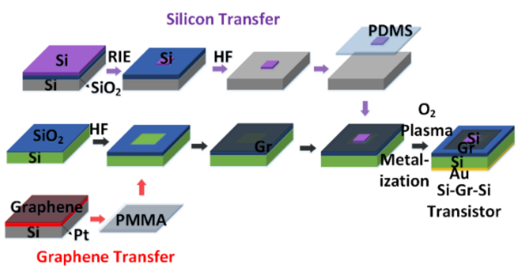

Fig. 2 An illustration for the fabrication of a Si-Gr-Si transistor starting from patterning of an n-type Si substrate with a SiO_2 capping layer. Graphene and Si transfer were performed one after another. The Si-Gr-Si structure was formed through the window of the SiO_2.

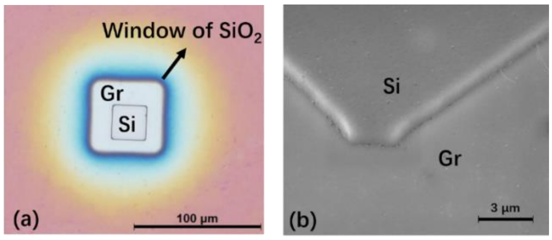

Fig. 3 (a) Optical and (b) SEM images for a Si-Gr-Si transistor.

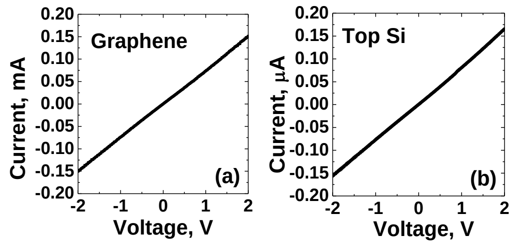

Fig. 4 Ohmic contact characteristics between (a) the graphene and the probe, and (b) the top Si and the probe. Two probes directly touched the graphene or the top Si with a distance of 54.0 µm. The relative small current in (b) could be understood from a current-conduction-route point of view in the measurement and did not limit the transistor current since a different current conduction route when the transistor was turned on.

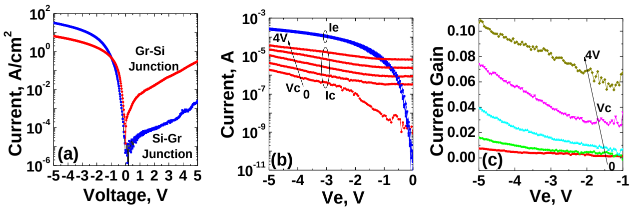

Fig. 5 (a) Characteristics of the top Si-Gr emitter junction and the Gr-bottom Si collector junction. (b) Input and transfer characteristics of a typical Si-Gr-Si transistor in the common-base mode. (c) Common-base current gain excluding the effect of the leakage current of the collector junction.

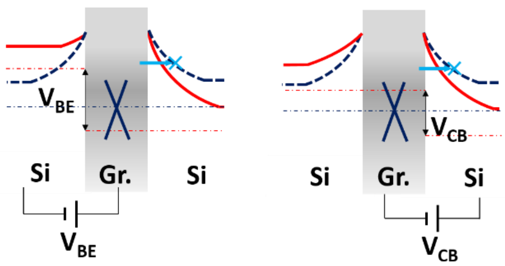

Fig. 6 An illustration for the current and the current gain changing with increased biases considering the quantum capacitance effect of graphene. The increased biases V_{BE} and V_{CB} resulted a decreased electron tunnel distance at the collector junction leading to an increased current gain. Conduction bands were shown (blue dash line: before bias. Red solid line: after bias).