RESEARCH ARTICLE

Improved Graphene-base Heterojunction Transistor with Different Collector Semi-conductors for High-frequency Applications

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A new kind of transistor device with a graphene monolayer embedded between two n-type silicon layers is fabricated and characterized. The device is called graphene-base heterojunction transistor (GBHT). The base-voltage controls the current of the device flowing from the emitter via graphene to the collector. The transit time for electrons passing by the ultrathin graphene layer is extremely short which makes the device very promising for high frequency RF-electronics. The output current of the device is saturated and clearly modulated by the base voltage. Further, the silicon collector of the GBHT is replaced by germanium to improve the device performance. This enabled the collector current to be increased by almost three orders of magnitude. Also, the common-emitter current gain (I_c/I_b) increased from 10^{-3} to approximately 0.3 for the newly designed device. However, the ON-OFF ratio of the improved germanium based GBHT has so far been rather low. Further optimizations are necessary in order to fully exploit the potential of the graphene-base heterojunction transistor.

Introduction

In order to achieve cut-off frequencies in the terahertz (THz) range the graphene-base heterojunction transistor (GBHT) has been proposed [**1**]. The novel transistor exhibits a graphene monolayer embedded between two n-doped silicon layers. The structure of the device is similar to an NPN silicon bipolar transistor with the p-type silicon base being replaced by a monolayer of graphene. The innovative device structure exhibits a vertical arrangement of emitter (E), base (B) and collector (C). Due to the ultimately thin graphene base the transit time for electrons passing through the base is very low potentially allowing for very high cut-off frequencies (f_T). Key elements of the GBHT are the Schottky barriers (height $q\Phi_B$) between n-silicon and graphene [**2**]. At equilibrium, a depletion layer is formed both in the emitter and collector regions close to the graphene base. This leads to the formation of a quasi-triangular barrier between emitter and collector whose height is controlled by the base-emitter voltage. In the off-state, charge carriers are blocked by a barrier. In the on-state, the quasi-triangular barrier is reduced by the forward-biased emitter-base junction. Now, the electrons injected by the emitter can move via the base to the collector. The current in the GBHT flows vertically through the graphene, while the current in graphene field-effect transistors (GFET [**3**]) flows in the plane of the graphene monolayer. For GBHT's, a better current saturation and high frequency performance are expected compared to GFET's.

First attempts were made recently to put the GBHT into practice by means of amorphous silicon emitter and collector layers or crystalline silicon collector layers [**4,5**]. In this study, improved device performance with increased output current and common-emitter current gain are demonstrated. To achieve this improvement, the n-silicon collector was replaced by n-germanium.

Experimental

As a substrate for the GBHT a 300µm thick lightly doped (1 - 5 Ohmcm) n-type silicon floatzone wafer or a n-type (5 - 40 Ohmcm) germanium wafer were used. A 60 nm thick Al_2O_3 layer was deposited by atomic layer deposition to electrically separate the graphene base contact from the wafer substrate. An area of 0.01 cm² was exposed afterwards by wet chemical etching in hydrofluoric acid (5 %). Subsequently, commercially available CVD grown graphene was transferred to the exposed area by a standard

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wet chemical transfer approach [5]. On top of the graphene monolayer, a 100 nm thick n-type amorphous silicon layer was deposited by VHF-PECVD (140 MHz) using a shadow mask. The increased plasma excitation frequency was necessary to avoid damage to the underlying graphene [6]. A gas mixture of silane, hydrogen and phosphine was used during the PECVD process. The substrate temperature was kept constant at 180°C. A thin highly doped n-type layer was deposited on top of the semiconducting emitter in order to ensure an ohmic contact to the emitter metallization. The base, collector and emitter metallization were fabricated via electron beam evaporation using shadow masks.

IV measurements were carried out with three source measure units from Keithley Instruments (K236, K237, K238). The output characteristics were measured for certain fixed base voltages (V_{be}) while sweeping V_{ce} and measuring I_c. Gummel plots were also collected and shown for V_{cb} = 0V.

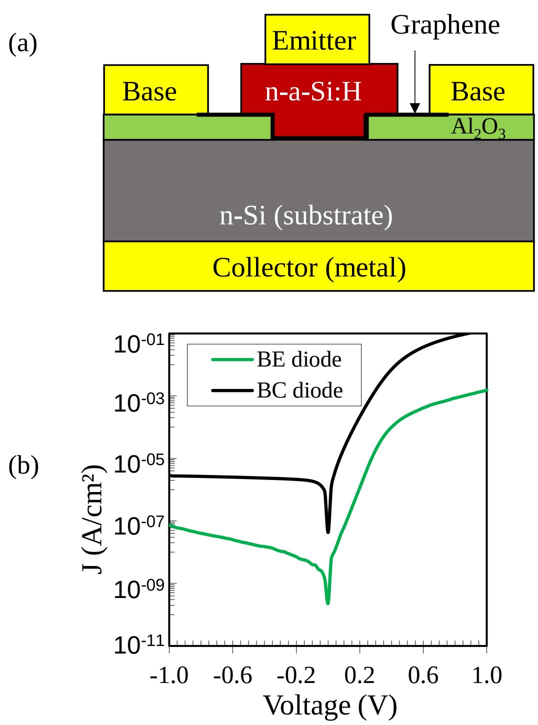


Fig. 1. (a) Structure of the graphene-base heterojunction transistor with an n-type silicon collector, (b) Semi logarithmic IV plots of the Base-Emitter (BE - green curve) and Base-Collector (BC – black curve) diode currents.

Results and discussion

Fig. 1(a) shows the structure of the GBHT with the n-type silicon collector. The graphene flake is transferred to the exposed n-Si area and is metallized with base contacts. Aluminium oxide (Al_2O_3) is used as an insulator to separate the base metallization from the n-Si substrate. The current of the device is controlled by the base voltage and flows vertically from the emitter via graphene to the collector. This is a major difference to other graphene devices (e.g., GFET), where the current flows horizontally in the graphene plane. The IV curves of the individual base-emitter diode (BE) and base collector diode (BC) of the transistor are illustrated in **Fig. 1(b)**. While good ON/OFF ratios where achieved for both the BE and BC diode, a large asymmetry of the individual diode currents can be observed. Thereby, the BC diode exhibits a higher reverse current than the BE diode. This can be attributed to copper residues on the BC interface, which cannot be completely avoided during the wet transfer of graphene. These copper residues between silicon and graphene can reduce the Schottky barrier height, which leads to increased diode currents.

In **Fig. 2(a)** the common-emitter output characteristics of the GBHT device is shown. A clear modulation of the collector current as a function of V_{be} can be observed. The collector current of the device is saturated for increased V_{ce} values. Compared to the previous device generation [5], the output current (J_c) and the common-emitter current gain (J_c/J_b) of the GBHT could be increased by about one order of magnitude. This was achieved through optimized cleaning of the graphene surface before the n-a-Si:H deposition. In **Fig. 2(b)** the Gummel plot for V_{cb} = 0 V is given. It can be seen, that the collector current is still much lower than the base current in the entire investigated V_{be} range. Thus, the common-emitter current gain ß of the prototype device remains at around 10^{-3}. The emitter and collector pin of the device have also been exchanged but the current gain of this inverted GBHT was very low, too. This configuration also led to device instabilities as the a-Si:H/graphene diode tends to breakthrough when biased with increased reverse voltages.

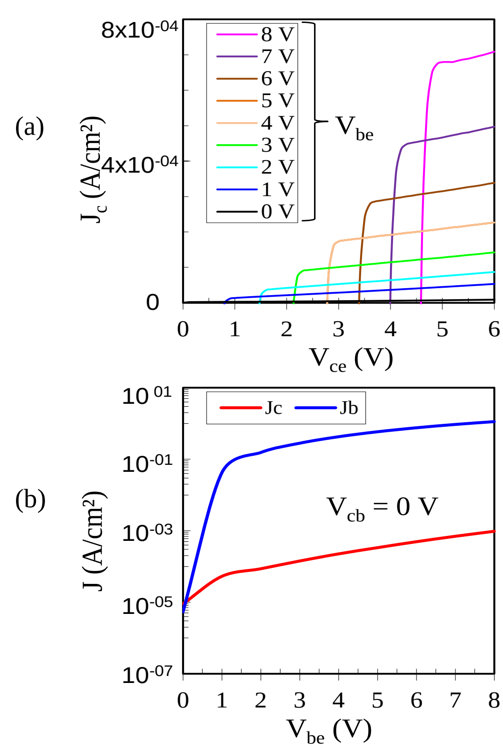


Fig. 2. (a) Common-emitter output characteristics of the silicon-based GBHT with V_{be} varied from 0V to 8V. (b) Gummel plot of the GBHT for V_{cb} = 0V.

For comparison, a reference transistor with a p-type silicon base was also fabricated and characterized [**5**]. A much higher output current ($J_c \approx 5x10^{-1}$ A/cm² at $V_{be} = 1$ V) is achieved for the reference silicon NPN transistor compared to the GBHT ($7x10^{-4}$ A/cm² at $V_{be} = 8$V). In contrast to the GBHT, J_c of the reference transistor increases sharply at low base voltages applied ($V_{be} < 1$V). In addition, the collector current exceeds the base current, resulting in a common-emitter current gain of larger than 1 ($ß_{max} = I_c / I_b = 7$). The good functionality of the NPN silicon reference transistor demonstrates, that in principle it is possible to produce high quality heterojunction transistors by the combination of n-a-Si:H and n-type crystalline silicon.

From the results so far it can be seen that the GBHT behaves more like a metal-base transistor (originally known for low gain values [**7**]) than like an NPN bipolar transistor. Thereby, mainly four physical effects reduce the gain of metal-base transistors (MBT):

a) Electron-phonon interaction in the emitter semiconductor
b) Base transport loss due to scattering of electrons in the metal film
c) Electron-phonon backscattering in the collector semiconductor
d) Quantum-mechanical reflection of electrons at the metal-collector semiconductor barrier

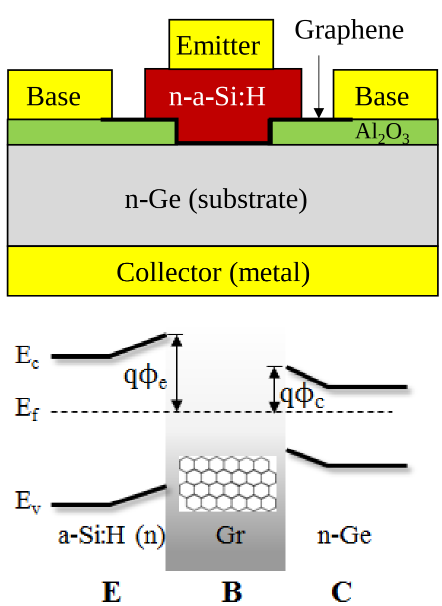
(a)
(b)


Fig. 3. (a) Structure of the GBHT utilizing an n-type germanium collector. (b) Band diagram of the germanium based GBHT with an asymmetrical structure ($q\Phi_e > q\Phi_c$).

Especially point (d) is the most important lever to increase the current gain of metal-base transistors. As stated by Sze *et. al.*, [**7**], the quantum-mechanical reflection of electrons at the metal-collector barrier depends on the Schottky barrier heights of the emitter-base and base-collector junctions. To reduce quantum-mechanical reflection, an asymmetrical structure with an emitter barrier ($q\Phi_e$) larger than the collector barrier ($q\Phi_c$) should be used. This can e.g., be realized by the combination of n-a-Si:H (emitter), graphene and n-germanium (collector). In this case the n-a-Si:H/graphene emitter Schottky barrier ($q\Phi_e$) is larger than the graphene/n-germanium collector barrier ($q\Phi_c$). **Fig. 3(a)** shows the structure of the GBHT utilizing a germanium collector. In **Fig. 3(b)** the band diagram of this asymmetrical device architecture ($q\Phi_e > q\Phi_c$) is shown.

Next, the novel germanium-based device was fabricated and analysed. In **Fig. 4(a)** the common-emitter output characteristics of the newly designed GBHT are shown. The collector current of the germanium-based device is much higher (> 10^{-1} A/cm²) than that of the silicon-based GBHT. Like in the case of the silicon-based GBHT the collector current of the germanium-based device scales with the base-emitter voltage V_{be}. However, the base-collector leakage current ($V_{be} = 0$ V) is quite high, which leads to a poor ON/OFF ratio (< 10). Further optimization is necessary to improve the BC junction of the device. This can be realized for example by lateral downscaling of the GBHT or improved interface treatments of the n-germanium wafer before the graphene transfer. In **Fig. 4(b)** the Gummel plot of the germanium-based GBHT is shown. As can be seen, the collector current is much closer to the base current compared to the silicon-based GBHT. Thus, the common-emitter current gain of the germanium-based GBHT is approximately 0.3.

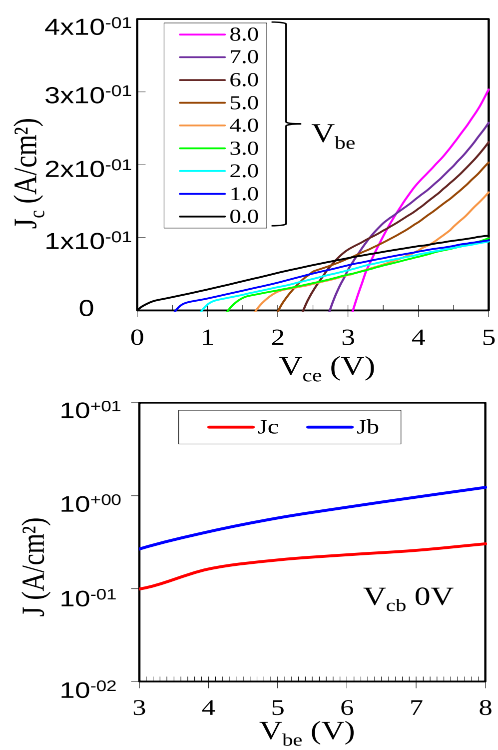
(a)
(b)


Fig. 4. (a) Common-emitter output characteristics of the germanium-based GBHT. (b) Gummel plot of the germanium-based transistor showing J_c (V_{be}) and J_b (V_{be}) for $V_{cb} = 0$V.

In a first theoretical GBHT study by DiLecce *et. al.*, [**1**] it is argued that the GBHT can be viewed as a descendent of the NPN bipolar transistor with similar DC performance of the device. High collector currents at low base-emitter voltages (V_{be}) were achieved. A common-emitter gain of larger than one and THz cut-off frequencies were achieved, as well.

The silicon-based GBHT developed in this study with limited collector currents (≈ $7x10^{-4}$ A/cm²) and limited gain stays far behind the predicted performance. At the current stage of development, the novel GBHT does not resemble an NPN bipolar transistor, but rather behaves like a metal-base transistor.

This is intuitively understandable because graphene, which is used here as a base material, has semi-metallic properties. Although treated as potential high-speed devices, early MBT's suffered from low gain values. Improved current gain was achieved by novel material combinations with asymmetrical Schottky barriers at the emitter-base and base-collector interface ($q\Phi_e > q\Phi_c$) [**8,9**]. On the other hand, the silicon-based GBHT fabricated in this study exhibits a symmetrical device architecture ($q\Phi_e \approx q\Phi_c$).

In fact, the n-a-Si:H/graphene Schottky barrier [**10**] has almost the same height as the graphene/n-silicon barrier [**11**]. As stated above, this leads to an increased quantum-mechanical reflection of electrons at the base-collector interface. This partly explains the low collector current and gain of the silicon-based GBHT.

By using an asymmetrical structure ($q\Phi_e > q\Phi_c$) with an a-Si:H emitter and a germanium substrate the collector current and gain could be strongly increased. Nevertheless, the base-collector leakage current must be significantly reduced in order to utilize the full potential of the novel graphene-base heterojunction transistor.

Conclusion

A novel graphene-base heterojunction transistor with an n-a-Si:H emitter layer and an n-silicon/n-germanium collector was fabricated and analyzed. A clear modulation of the output current as a function of the base-emitter voltage could be observed for both the silicon-based and germanium-based devices. Further, the transistor output current and gain could be strongly increased by changing the collector material to n-germanium. However, at present the base-collector leakage current of the germanium-based device is too high, which leads to a poor ON/OFF ratio. Lateral downscaling of the transistor and improved BC interface treatments are seen as the major levers to reduce the BC leakage current. We believe that after these optimizations a functional GBHT will be possible that will deliver a significant high-frequency performance.

Acknowledgements

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Conflicts of interest
There are no conflicts to declare.

Keywords

Amorphous silicon, graphene, germanium, high-frequency, transistor

References

(a) Scientific article

1. Di Lecce, V.; Grassi, R.; Gnudi, A.; Gnani, E.; Reggiani, S.; and Baccarani, G.; IEEE transactions on electron devices, **2013**, 60, 4263.
https://doi.org/10.1109/TED.2013.2285446
2. A. Di Bartolomeo, Physics Reports, **2016**, 606, 1.
https://doi.org/10.1016/j.physrep.2015.10.003
3. Wu, Y.; Lin, Y.-M.; Bol, A.A.; Jenkins, K.A.; Xia, F.; Farmer, D.B.; Zhu, Y.; and Avouris, P.; *Nature*, **2011**, *472*, 7341, 74.
https://doi.org/10.1038/nature09979
4. Chavarin, C.A.; Strobel, C.; Kitzmann, J.; Di Bartolomeo, A.; Lukosius M.; Albert, M.; Bartha J.W.; and Wenger Ch.; *Materials*, **2018**, 11 (3), 345.
https://doi.org/10.3390/ma11030345
5. Strobel, C.; Chavarin, C.A.; Leszczynska, B.; Leszczynski, S.; Winkler, F.; Killge, S.; Völkel, S.; Richter, K.; Hiess, A.; Knaut, M.; Reif, J.; Albert, M.; Wenger, Ch.; and Bartha, J.W.; *J. Appl. Phys.*, **2019**, *125*, 234501.
https://doi.org/10.1063/1.5093167
6. Lupina, G.; Strobel, C.; Dabrowski, J.; Lippert, G.; Kitzmann, J.; Krause, H. M.; Wenger, Ch.; Lukosius, M.; Wolff, A.; Albert, M.; and Bartha, J. W.; *Appl. Phys. Lett.*, **2016**, 108, 193105.
https://doi.org/10.1063/1.4948978
7. Sze, S.M.; Gummel, H.K.; *Solid-State Electronics*, **1966**, 9, 751.
https://doi.org/10.1016/0038-1101(66)90116-X
8. Meruvia, M.S.; Hümmelgen, I.A.; Sartorelli, M.L.; Pasa, A.A.; and Schwarzacher, W.; *Appl. Phys. Lett.*, **2004**, 84, 3978.
https://doi.org/10.1063/1.1751218
9. Liu, C.; Ma, W.; Chen, M.; Ren, W.; and Sun, D.; *Nature Communications*, **2019**, 10, 4873.
https://doi.org/10.1038/s41467-019-12814-1
10. Strobel, C.; Chavarin, C.A.; Kitzmann, J.; Lupina, G.; Wenger, Ch.; Albert, M.; and Bartha, J.W.; *J. Appl. Phys.*, **2017**, 121, 245302.
https://doi.org/10.1063/1.4987147
11. Mohammed, M.; Li, Z.; Cui, J.; Chen, T.-pin; *Nanoscale Research Letters*, **2012**, 7, 302.
https://doi.org/10.1186/1556-276X-7-302

(b) Book
None

(c) Book Chapter
None

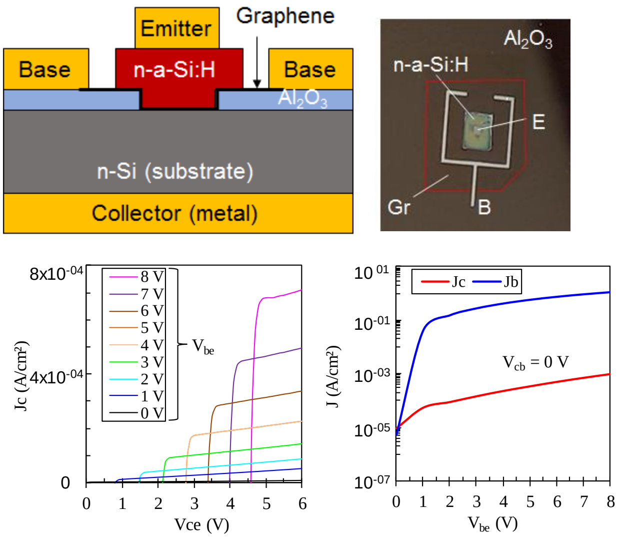
(d) Patent
None

(e) Meeting/Conference/Symposium Abstract:
None

Authors biography

Carsten Strobel is currently senior scientist at the Technical University of Dresden. He earned his Diploma at TU-Dresden in 2005 and his PhD in engineering at the Technical University of Dresden in 2012, working with Prof. Johann Bartha. In his thesis work, he pioneered the dynamic deposition of amorphous and microcrystalline silicon thin film solar cells. After completing his PhD, Mr. Strobel accepted a position at TU-Dresden under Prof. Bartha at the chair of semiconductor technology. During that time, he also began to work with the 2D material graphene. In particular he focused on the development of bipolar like transistors with a graphene base instead of a silicon base. He could demonstrate that such novel graphene-base heterojunction transistors are operational.

Graphical abstract



The graphene-base heterojunction transistor GBHT is an attractive device concept to reach THz operation frequencies. The novel transistor consists of two n-doped silicon layers with a graphene monolayer in between. Here we demonstrate improved device performance with current saturation in the transistor's output characteristics. A clear modulation of the collector current by the applied graphene base voltage can be observed.

Novelty statement

The results presented in the following research article are original and have not been published elsewhere before. The combination of n-type amorphous silicon (emitter), graphene (base) and n-type germanium (collector) is unique in the field of 2D/3D hot-electron transistors. The improved device performance with strongly increased output currents is a further milestone towards future high-speed transistors for RF applications. Alternative approaches rely on transistor architectures with n-type crystalline silicon emitters. However, these transistors are much more difficult to fabricate and to scale up.

References

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