Graphene Hot Electron Transistors

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Abstract
Graphene has been investigated intensely as a next-generation electronic material since the presence of the field effect was reported in 2004 [1]. The absence of a band gap and the resulting high off-state leakage currents prohibit graphene as the channel material in field effect transistors (FETs) for logic applications [2]. Several alternative graphene device concepts have been proposed that rely on quantum mechanical tunneling. These include graphene / hexagonal boron nitride superlattices [3] or (gated) graphene / semiconductor Schottky barriers [4, 5]. Along these lines, we recently proposed a Graphene Base Transistor (GBT) [6], a hot electron transistor (HET) [7-9] with a base contact made of graphene that can potentially deliver superior DC and RF performance [6] (Figure 1). HETs with metallic bases are limited by two mechanisms: carrier scattering and "self-bias crowding" (in-plane voltage drop) in the base material. Optimization becomes a trade-off, since thinning the metal-base reduces scattering, but increases the metal-base resistance and the self-bias crowding [7]. Graphene is thus the ideal material for HET bases due to its ultimate thinness and high conductivity.

We experimentally demonstrate DC functionality of graphene-based hot electron transistors, which we call Graphene Base Transistors (GBT, Figure 1). The fabrication scheme is potentially compatible with silicon technology and can be carried out at the wafer scale with standard silicon technology [10]. The state of the GBTs can be switched by a potential applied to the transistor base, which is made of graphene. Figure 2 shows schematic band structures for an unbiased device (a) and a biased device in the off- (b) and in the on-state (c). In the on-state, Fowler-Nordheim tunneling leads to the injection of hot carriers into the conduction band of the base-collector insulator. Measured transfer characteristics of the GBTs show ON/OFF current ratios exceeding 10^4 (Figure 3a, [11]). Theoretical calculations predict that ON/OFF current ratios of over five orders of magnitude and operation up to the THz frequency range can be obtained with GBTs [6] (Figure 3b). Temperature dependent measurements will be discussed in the talk and confirm the predicted tunneling mechanism.

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References

[1] K. S. Novoselov, A. K. Geim, S. V. Morozov, D. Jiang, Y. Zhang, S. V. Dubonos, I. V. Grigorieva, and A. A. Firsov, "Electric Field Effect in Atomically Thin Carbon Films," *Science,* vol. 306, pp. 666-669, October 22, 2004 2004.

[2] M. C. Lemme, T. J. Echtermeyer, M. Baus, and H. Kurz, "A Graphene Field-Effect Device," *IEEE Electron Device Letters,* vol. 28, pp. 282-284, 2007.

[3] L. Britnell, R. V. Gorbachev, R. Jalil, B. D. Belle, F. Schedin, A. Mishchenko, T. Georgiou, M. I. Katsnelson, L. Eaves, S. V. Morozov, N. M. R. Peres, J. Leist, A. K. Geim, K. S. Novoselov, and L. A. Ponomarenko, "Field-Effect Tunneling Transistor Based on Vertical Graphene Heterostructures," *Science,* vol. 335, pp. 947-950, February 24, 2012 2012.

[4] S. Tongay, M. Lemaitre, T. Schumann, K. Berke, B. R. Appleton, B. Gila, and A. F. Hebard, "Graphene/GaN Schottky diodes: Stability at elevated temperatures," *Applied Physics Letters,* vol. 99, pp. 102102-3, 2011.

[5] H. Yang, J. Heo, S. Park, H. J. Song, D. H. Seo, K.-E. Byun, P. Kim, I. Yoo, H.-J. Chung, and K. Kim, "Graphene Barristor, a Triode Device with a Gate-Controlled Schottky Barrier," *Science,* vol. 336, pp. 1140-1143, June 1, 2012 2012.

[6] W. Mehr, J. C. Scheytt, J. Dabrowski, G. Lippert, Y.-H. Xie, M. C. Lemme, M. Ostling, and G. Lupina, "Vertical Transistor with a Graphene Base," *IEEE Electron Device Letters,* vol. 33, pp. 691-693, 2012.
[7] C. A. Mead, "Operation of Tunnel-Emission Devices," *Journal of Applied Physics,* vol. 32, pp. 646-652, 1961.
[8] M. Heiblum, "Tunneling hot electron transfer amplifiers (theta): Amplifiers operating up to the infrared," *Solid-State Electronics,* vol. 24, pp. 343-366, 1981.
[9] T. Yajima, Y. Hikita, and H. Y. Hwang, "A heteroepitaxial perovskite metal-base transistor," *Nature Materials,* vol. 10, pp. 198-201, 2011.
[10] S. Vaziri, G. Lupina, A. Paussa, A. D. Smith, C. Henkel, G. Lippert, J. Dabrowski, W. Mehr, M. Östling, and M. C. Lemme, "A Manufacturable Process Integration Approach for Graphene Devices," *accepted for publication: Solid State Electronics,* 2013.
[11] S. Vaziri, G. Lupina, C. Henkel, A. D. Smith, M. Östling, J. Dabrowski, G. Lippert, W. Mehr, and M. C. Lemme, "A Graphene-based Hot Electron Transistor," *http://arxiv.org/abs/1211.2949,* 2012.

Figures

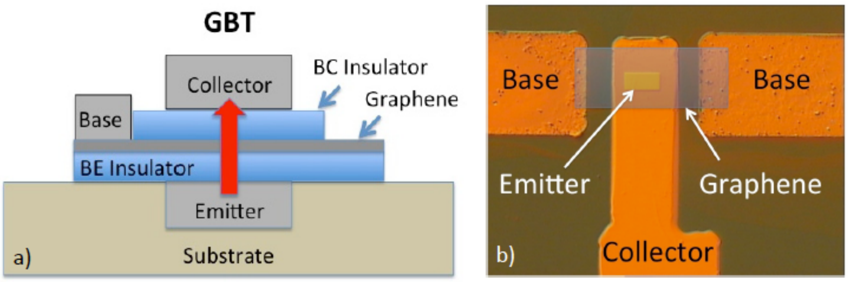

Figure 1: a) Schematic and b) optical micrograph (top view) of a graphene hot electron transistor (HET).

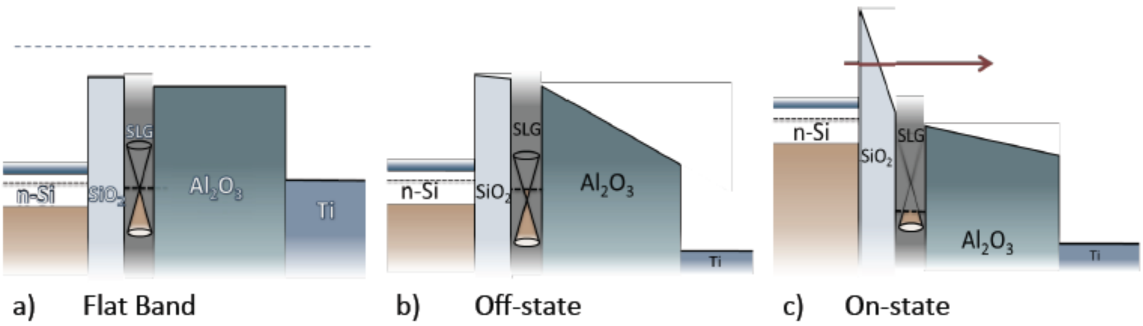

Figure 2: Schematic band structure of a graphene HET. a) unbiased, b) Off-state with finite collector bias and no base bias and c) On-state with finite collector V_c and base voltage V_b (V_c>V_b).

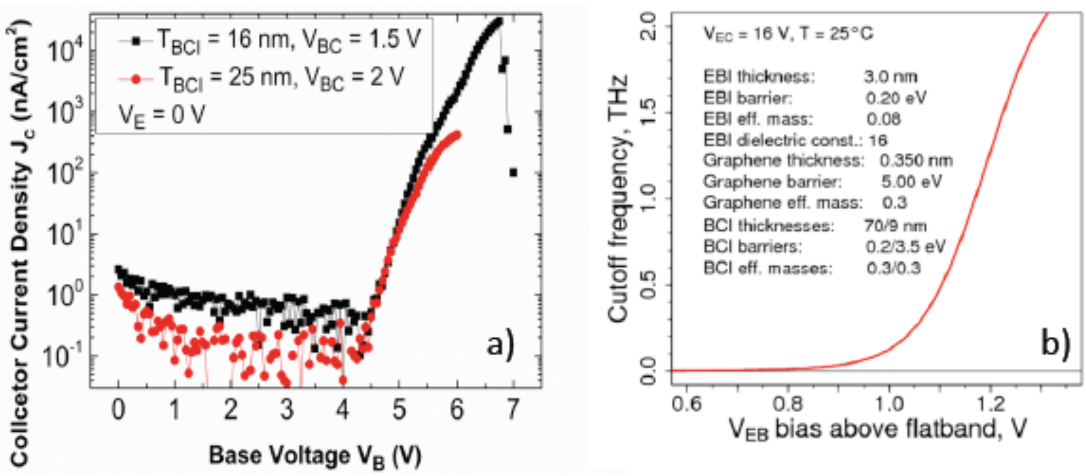

Figure 3: a) Measured transfer characteristics of two graphene HETs with an On-Off ratio of 10^3 and $5x10^4$. b) Simulated cutoff frequency for a graphene HET with optimized dielectric barriers [6].