Abstract—We present a novel graphene-based-device concept for a high-frequency operation: a hot-electron graphene base transistor (GBT). Simulations show that GBTs have high current on/off ratios and high current gain. Simulations and small-signal models indicate that it potentially allows terahertz operation. Based on energy-band considerations, we propose a specific material solution that is compatible with SiGe process lines.

Index Terms—Graphene, hot-electron transistor (HET), radio frequency (RF).

I. INTRODUCTION

Carbon-based materials may enhance the performance of digital and radio frequency (RF) electronics [1]. Extensive research has been devoted to exploit the exceptional properties of graphene in field-effect transistors with a graphene channel (GFETs) [2], [3]. This has resulted in RF GFETs with transition frequencies (fT) of several hundred gigahertz [4], [5], ambipolar RF mixers [6], and frequency multipliers [7]. However, GFETs are not suitable for logic applications due to the absence of a bandgap, and the lack of a pronounced drain-current saturation limits their potential for conventional RF amplifying circuits [8], [9].

We propose an alternative application of graphene as an extremely thin and highly conductive electrode for a hot-electron transistor (HET) with a graphene base. This graphene base transistor (GBT) combines the concept of HETs [10]–[12] with the unique properties of graphene to result in a high-frequency (HF) device that offers low off currents (Ioff), drain-current saturation, and power amplification.

II. GBT CONCEPT

Fig. 1(a) and (b) illustrates the difference between the GFET and the GBT. Charge carriers traverse the graphene in the GFET laterally. The GBT is based on a vertical arrangement of emitter (E), base (B), and collector (C), just like a HET or a vacuum triode. In the OFF state, the carriers face a barrier [cf. the simplified band diagram in Fig. 1(c)]. Note that although graphene has no bandgap for lateral transport, it poses a barrier for transport in the normal direction (bandgap at Γ [13]). In the ON state, carriers tunnel through the emitter–base (E–B) insulator (EBI) and the base control electrode (graphene) into the conducting band of the base–collector (B–C) insulator [(BCI); Fig. 1(d)].

There are substantial advantages when using graphene as the base material: The monatomic thickness favors ballistic transport across the base and a homogenous electric field at the base interface. Assuming that only electrons scattered within the base contribute to the base current (IB), this should reduce IB by two orders of magnitude compared to similar HETs with a metal base. In contrast to metals, the base resistivity is not
limited by pinholes; values around 100 Ω/sq are achievable [14]. Graphene is chemically inert, reducing issues with process-induced interface reactions. Although the inhomogeneity of graphene doping may lead to inhomogeneous I_C and to local heating, this may be uncritical thanks to the high thermal conductivity of graphene.

### III. DEVICE DESIGN ASPECTS

GBT needs to be carefully engineered for an optimal operation. The EBI must be thin to yield high output currents. The EBI barrier \( \Phi_{\text{EBI}} \) is controlled by the E–B voltage (\( V_{\text{EB}} \)) applied to the graphene. In the ON state, electrons must cross the BCI easily. However, for good power performance, the BCI should withstand \( V_{\text{BC}} \approx 10 \) V, which implies a high tunneling barrier. The structure shown in Fig. 1(e) addresses these issues. SiO_2 is used on the collector side, and a graded silicate is used on the base side. In the graded part, the dielectric constant and the BCI barrier (\( \Phi_{\text{BCI}} \)) vary with the distance from the base. This can be achieved with a gradually decreasing metal content across the dielectric [15]. The barrier on the collector side is controlled by the B–C voltage \( V_{\text{BC}} \). When \( V_{\text{BC}} \) is high enough, most of the electrons encounter no barrier [Fig. 1(e)]. SiO_2 thickness allows for high output voltages, i.e., for good power performance. This reveals the several advantages of the GBT compared to GFETs: 1) GBTs allow for high \( I_{\text{on}} / I_{\text{off}} \) current ratios [Fig. 3(b) and (c)]; 2) GBTs show current saturation in the output characteristics for high \( V_{\text{EC}} \), nearly all electrons travel above the BCI barrier. Thus, \( I_{\text{on}} \) is limited by the EBI barrier and independent of \( V_{\text{EC}} \) [Fig. 1(j)]; and 3) Tunneling is a fast process. Even at 2.5 THz, the current response of a tunneling diode resembles the dc curve. With the transport distance below 100 nm, delays due to diffusion should stay below a picosecond [16].

### IV. SS MODELING AND COMPARISON WITH HBT

A terahertz transistor may work as an HF linear small-signal (SS) amplifier. SS models with and without parasitics are shown in Fig. 2(a) and (b). The transconductance \( g_m \) becomes

\[
g_m = \frac{\partial i_C}{\partial v_1} = \frac{\beta_0}{\beta_b + 1} \frac{\partial i_E}{\partial v_1} \approx \frac{\partial i_E}{\partial v_1} \tag{1}
\]

where \( v_1 \) is the SS voltage (i.e., \( V_{\text{BE,ac}} = V_{\text{BE,dc}} + v_{1,ac} \) and the amplitude of the ac signal \( v_1 \) is small), \( i_c \) and \( i_b \) are the SS collector and base currents, respectively, and \( \beta_0 = i_c / i_b \gg 1 \) is the SS current gain.

The HF-SS model [Fig. 2(b)] assumes metallic emitter and collector, and graphene base. \( R_B \) denotes the resistance of the base contact and of the graphene layer, \( R_C \) and \( R_E \) represent the collector and emitter resistances, \( r_\pi \) and \( r_\mu \) are the differential resistances of EBI and BCI, and \( C_\pi \) and \( C_\mu \) are their plate capacitances. \( C_Q = |\partial Q_B / \partial v_Q| = \kappa |V_Q| \) is the quantum capacitance of graphene \( \kappa = 25 \) μF/cm²/V [17]. \( Q_B \) is the charge accumulated in graphene, and \( v_Q \) has the physical meaning of the Fermi energy in graphene, measured with respect to the Dirac point [DP; Fig. 2(c)–(e)]. Neglecting the substrate capacitance \( C_s \) and delays due to the diffusion of carriers, the frequency response is

\[
\tau = \frac{dQ_B}{db_C} = \frac{C_{\text{TOT}}}{C_C(\pi + \mu)} \quad f_T = \frac{1}{2 \pi \tau} = \frac{1}{2 \pi} \frac{g_m}{C_{\text{TOT}}} \tag{2}
\]

\[
C_{\text{TOT}} = \frac{C_{\pi} + C_{\mu}}{C_{\pi} + C_{\mu} + C_B} \quad V_Q = \frac{C_{\pi} + C_{\mu}}{s \kappa} \left( 1 + 2 \kappa |C_{\pi} U_{\text{EB}} + C_{\mu} U_{\text{CB}}| / (C_{\pi} + C_{\mu})^2 \right) - 1 \tag{3}
\]

with \( s = \text{sign}(C_{\pi} U_{\text{EB}} + C_{\mu} U_{\text{CB}}) \), \( U_{\text{EB}} = V_{\text{EB}} - \Delta W \), \( U_{\text{CB}} = V_{\text{CB}} + \Delta W \), and \( U_{\text{EC}} = V_{\text{EB}} - V_{\text{EC}} \). The accumulated charge is \( Q_B = 1/2 s \kappa V_Q^2 \). For the metallic base, one obtains \( C_{\text{TOT}} = C_{\pi} + C_{\mu} \) [18]; \( V_Q \) is then zero.

### V. QUANTUM-MECHANICAL SIMULATIONS

Graphene is semimetallic, with the DP in the corner of the 2-D first Brillouin zone (high lateral momentum). In the GBT, electrons tunnel through the EBI, and most of them are likely to enter the graphene with small lateral momentum. For such electrons, there is an energy gap in the graphene (at \( \Gamma \)). To verify if this makes graphene a tunneling barrier, we simulated the tunneling across the graphene placed between unbiased cobalt electrodes in vacuum. The self-consistent band structure obtained from ab initio atomistic calculations was used. The insertion of the graphene between the electrodes separated by 1.9 nm results in a tunneling spectrum that is roughly proportional to that obtained for 1.7-nm separation and no graphene. Thus, graphene slightly reduces the tunneling barrier strength. This is largely due to work function difference between cobalt and graphene: Graphene becomes positively charged so that the distance to vacuum energy decreases as the electron approaches the graphene sheet. A fully transparent or scattering-only sheet would reduce the vacuum thickness by about 0.35 nm (i.e., by the thickness of graphene) even without any work function difference. This does not happen; hence, graphene is a barrier, not a transparent layer.

We performed a quantum-mechanical simulation of the GBT. The tunneling parameters cannot be derived reliably from our atomistic data. For that reason, the simulation should be viewed as a zero-order estimate of a GBT in action. The Schrödinger equation with open-boundary conditions was solved numerically for one-band effective potential rounded up by image force at interfaces with emitter and collector. No self-consistent term was added as the distribution of the potential in the vicinity of graphene is not known exactly. No scattering effects were included; the temperature corresponds to the Fermi distribution of electron energies. We approximate the tunneling barrier as a rectangle with \( d = 0.35 \) nm and \( \Phi_B = 5 \) eV (the conduction band edge at \( \Gamma \) is between 3.7 and 7 eV [19], [20]). The effective mass was set to 0.3, a conservative value typical for, e.g.,
SiO₂. We performed the calculations with and without quantum capacitance effects. Quantum capacitance lowers $C_{TOT}$, increasing $f_T$. However, in a realistic device, $-C_{EB}U_{EB}$ will exceed $C_pU_{EB}$, hence, $Q_B > 0$. This reduces the electric field in EBI and increases the effective $\Phi_B$ [Fig. 3(a)], decreasing $g_m$ and, thus, also $f_T$. With increasing $\Delta W$, the $f_T$ degradation becomes less pronounced.

Fig. 3(b) and (c) shows the simulated transfer and output characteristics for operation as a power amplifier. These curves underscore the potential of the GBT, with the $I_C$ switching over several orders of magnitude [Fig. 3(b)] and $I_C$ saturation [Fig. 3(c)]. We estimate that for a terahertz operation [Fig. 3(d)] at $V_{EB} \approx 1$ V, the EBI should not be thicker than 3–5 nm, and its energy barrier $\Phi_{EB1}$, at no bias, should be 0.4 eV or less. In our estimations with $V_{EC} = 16$ V, the electric field in SiO₂ is close to the critical field and below the critical field in the rest of the BCI. Unpinned Er₃Ge₃/Ge is assumed for the emitter/EBI. This should be viable as the interface between Ge and a germanide can be unpinned by, e.g., P [21]. The work function of Er₃Ge₃, 4.05 eV, matches the electron affinity of Ge, 4.0 eV. Assuming that the Er₃Ge₃/Ge interface can be unpinned as efficiently as for PrGe/Ge, we take $\Phi_{EB1} = 0.2$ eV at no bias. For the graded part of the BCI, we use Ti₃Si₁₋ₓO₂. The barrier at graphene/TiO₂ is assumed the same as that at Ge/graphene [22]. Fig. 3(d) compares $f_T$ obtained without $C_Q$ influence ($C_Q \rightarrow \infty, V_Q \rightarrow 0$) and with $C_Q$ (using $\Delta W = 0.6$ V).

VI. CONCLUSION

A new device, GBT, has been proposed and analyzed. The key feature is the use of graphene as the base electrode in the HET configuration. Distinct advantages are that graphene is pinhole free and does not interact chemically with adjacent materials. Graphene is also a highly conductive one-atom thick film which does not scatter the electrons injected from the emitter to the base. Simulated GBT transfer characteristics show switching over several orders of magnitude, and output characteristics show clear saturation. We proposed and evaluated a specific material solution for GBT indicating the feasibility of a terahertz operation.

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