Bipolar Transistor Based on Graphane

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Abstract. Graphane is a semiconductor with an energy gap, obtained from hydrogenation of the two-dimensional graphene sheet. Together with the two-dimensional geometry, unique transport features of graphene, and possibility of doping graphene, p and n regions can be defined so that p-n junctions become feasible with small reverse currents. Our recent analysis has shown that an ideal I-V characteristic for this type of junctions may be expected. Here, we predict the behavior of bipolar junction transistors based on graphane. Profiles of carriers and intrinsic parameters of the graphane transistor are calculated and discussed.

1. Introduction
Graphene is an extended two-dimensional (2D) covalently bonded hydrocarbon. It is a fully saturated hydrocarbon derived from a single graphene sheet with formula C₆H₆. All of the carbon atoms are in sp³ hybridization forming a hexagonal network and the hydrogen atoms are bonded to carbon on both sides of the plane in an alternating manner. It has a relatively large direct energy gap of about 3.6eV [1-6]. The numerical estimate for the intrinsic carrier density of graphene turns out to be too low for practical applications [7]. One of the simplest ways to reduce the energy gap is to bring up hydrogen deficiency in graphane structure [7]. So we use C₆H₃ Structure. In this paper, we analyze a 2D bipolar transistor based on doping of a modified graphane sheet. The graphane structure is supposed to encompass hydrogen deficiency, with a typical stoichiometric composition of C₆H₆₋ₓ. We have used the tight-binding method to show how hydrogen deficiency may be exploited to reduce the band gap of graphane from 3.6eV down to about 1.1eV [7]. This increases the intrinsic carrier density and thereby the conductivity of doped graphane. Analysis of the junctions with the aid of Shockley’s law is done to obtain the profiles and behaviour of the corresponding bipolar transistor.

2. Analysis
Necessary parameters are calculated at 300K [7]. The density of states for conduction and valence bands are respectively $N_c=2.1\times10^{17}m^{-2}$ and $N_v=2.6\times10^{17}m^{-2}$, with the intrinsic carrier density of $n_i=4.5\times10^7m^{-2}$. Now, we proceed with a p-n bipolar junction transistor, with the dopant-concentrations in the emitter, base and collector respectively given by $N_E=2.0\times10^{15}m^{-2}$, $N_B=10^{14}m^{-2}$, and $N_C=10^{13}m^{-2}$. One can immediately use the relation $V_j=V_T\ln(N_D/N_B/n_i^2)$ with $V_T=K_BT/q$, to readily get $V_{jBE}=0.8340V$ and $V_{jBE}=0.6968V$ for emitter-base and base-collector junctions, respectively.

As we deal with 2D junctions, the analysis the electric field is different to that of bulk step junctions [7]. For this purpose, we need to divide the charge sheets into infinitely many thin wire line charges,
with constant charge densities $\lambda_i$ [7]. The partial electric field due to each line charge is $E_i(r) = \lambda_i / 2\pi \varepsilon r_i$, where $r_i$ is the distance from the charge wire. This model is illustrated in figure 1. Integrating from the electric field gives the potential distribution. Calculated total electric field over the surface of the transistor is demonstrated in figure 2. We also find the width of the deplation regions in the emitter, base and collector to be in the order of micrometer.

3. Current-voltage characteristics
Figure 3 represents a schematic of a pnp transistor biased in the common-base configuration. It also indicates all the relevant current components of the transistor in the circuit.

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**Figure 1.** Schematic diagram of a pnp bipolar transistor.

**Figure 2.** The electric field distribution in the graphene bipolar transistor.

**Figure 3.** Current components of the graphene pnp transistor.
In the neutral base region, the injected minority-carriers distribution (holes) is governed by the continuity equation, with the boundary conditions at the two edges of neutral region

\[
- \frac{p_n - p_{n0}}{\tau_p} - \mu_p E \frac{dp_n}{dx} + D_p \frac{d^2 p_n}{dx^2} = 0
\]  

(1.1)

\[
p_{n0}(x = x_{nE}) = n_{n0} \exp \left( \frac{qV_{ce}}{K_a T} \right)
\]  

(1.2)

\[
p_{n0}(x = w - x_{nC}) = n_{n0} \exp \left( \frac{qV_{ce}}{K_a T} \right)
\]  

(1.3)

The general solution to the above equation is given by

\[
p_n(x) = p_{n0} \exp \left( \frac{x + x_{nE}}{L_{p1}} \right) \left[ -\exp \left( \frac{w}{L_{p2}} \right) + \exp \left( \frac{q V_{ce}}{K_a T} + \frac{w}{L_{p2}} \right) + \exp \left( \frac{x_{nE} + x_{nC}}{L_{p2}} \right) - \exp \left( \frac{q V_{ce}}{K_a T} \frac{x_{nE} + x_{nC}}{L_{p2}} \right) \right] \times
\]

\[
\left[ \exp \left( \frac{w}{L_{p2}} + \frac{x_{nE} + x_{nC}}{L_{p1}} \right) \right] \left[ -\exp \left( \frac{w}{L_{p2}} + \frac{x_{nE} + x_{nC}}{L_{p2}} \right) \right]^{-1}
\]

\[
+ p_{n0} \exp \left( \frac{x}{L_{p2}} \right) \left[ -\exp \left( \frac{x_{nE}}{L_{p1}} \right) \right] \left[ 1 - \exp \left( \frac{q V_{ce}}{K_a T} \frac{x_{nE} + x_{nC}}{L_{p2}} \right) \right] \times
\]

\[
\left[ \exp \left( \frac{w - x_{nC}}{L_{p2}} + \frac{x_{nE}}{L_{p1}} \right) - \exp \left( \frac{w - x_{nC}}{L_{p2}} + \frac{x_{nE}}{L_{p2}} \right) \right]^{-1}
\]  

(2)

The hole density in the base region is used for calculation of hole current due to the collector and emitter depletion regions. The electron currents at the emitter edge \(J_{nE}\) and the collector edge \(J_{nC}\) are given by

\[
J_{nE} = -q D_n \left. \frac{dn_n}{dx} \right|_{x=x_{nE}} = \frac{q D_n n_{p0}}{L_{n2}(x)} \left[ \exp \left( \frac{q V_{ce}}{K_a T} \right) - 1 \right] \exp \left( \frac{x_{nE} + x_{nC}}{L_{n2}} \right) \left. \right|_{x=x_{nE}}
\]  

(3.1)

\[
L_{n2}(x) = \left[ \frac{H_n}{2 D_n} E(x) + \sqrt{\left[ \frac{H_n}{2 D_n} E(x) \right]^2 + \frac{1}{\tau_n D_n}} \right]^{-1}
\]  

(3.2)

\[
J_{nC} = -q D_n \left. \frac{dn_n}{dx} \right|_{x=x_{nC}} = \frac{q D_n n_{p0}}{L_{n1}(x)} \left[ \exp \left( \frac{q V_{ce}}{K_a T} \right) - 1 \right] \exp \left( \frac{x - (w + x_{n0})}{L_{n1}} \right) \left. \right|_{x=x_{nC}}
\]  

(3.3)

\[
L_{n1}(x) = \left[ \frac{H_n}{2 D_n} E(x) - \sqrt{\left[ \frac{H_n}{2 D_n} E(x) \right]^2 + \frac{1}{\tau_n D_n}} \right]^{-1}
\]  

(3.4)

The emitter and collector currents can be then obtain from

\[
J_E = J_{nE} + J_{pE}
\]  

(4.1)

\[
J_C = J_{nC} + J_{pC}
\]  

(4.2)

Here \(J_{pE}\) and \(J_{pC}\) are minority-carriers current densities in the base region, flowing to emitter and collector regions, respectively. Figure 4 shows a typical collector current characteristics, which
confirms the exponential current-voltage dependence of the graphane transistor. Here, the collector-base junction is biased at $V_{CB} = -1\text{V}$. Figure 5 shows a representative set of output characteristics for the common base configuration.

![Graph showing collector current versus emitter-base voltage.](image)

**Figure 4.** Collector current characteristics versus emitter-base voltage.

![Graph showing output characteristics for common base configuration.](image)

**Figure 5.** Output characteristics for common base configuration.

### 4. Conclusions
We have introduced a 2-D p’np bipolar transistor based on graphane with hydrogen deficiency to reduce the band gap effectively. Using a basic analysis, we have shown that, within the approximation of the Shockley’s law of junctions, an exponential ideal I–V characteristic is expectable. Furthermore, we have calculated the surface distribution of electric field in the vicinity of the junction. Curvature of collector current characteristics shows good agreement with an ideal bipolar transistor.

### References
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