The formation of a p–n junction in a polymer electrolyte top-gated bilayer graphene transistor

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Abstract
We show simultaneous p- and n-type carrier injection in a bilayer graphene channel by varying the longitudinal bias across the channel and the top-gate voltage. The top gate is applied electrochemically using solid polymer electrolyte and the gate capacitance is measured to be 1.5 μF cm⁻², a value about 125 times higher than the conventional SiO₂ back-gate capacitance. Unlike the single-layer graphene, the drain–source current does not saturate on varying the drain–source bias voltage. The energy gap opened between the valence and conduction bands using top- and back-gate geometry is estimated.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

In recent years, single- and a few-layer graphene are at the center stage of intense research to unravel the physical properties of these new forms of carbon, with an eye on device applications. Ultrahigh mobilities and observation of ballistic transport make graphene-based devices a potential alternative for silicon-based devices [1–4]. The zero energy gap between the valence and conduction band in the energy spectrum of single-layer graphene (SLG) makes it difficult to achieve a high on–off ratio in field effect transistors (FET). On the other hand, bilayer graphene (BLG) devices hold greater promise in terms of better device performance with larger on–off ratio. This is feasible because of the bandgap opening due to the breaking of inversion symmetry of the two layers in an otherwise gapless energy band structure. Moreover, this gap between the conduction and valence band can be tuned by means of an external gate electric field, as demonstrated both theoretically [5–9] and experimentally [10–13]. In particular, Zhang et al [13] have reported a direct observation of the bandgap in the bilayer by infrared absorption. They have used dual-gate bilayer FET where an 80 nm Al₂O₃ film was used as the top gate and 285 nm SiO₂ as the back gate.

Misewich et al [14] have shown that it is possible to get polarized infrared optical emission from a carbon nanotube FET by creating an effective forward-biased p–n junction along the nanotube channel. This was achieved by applying the gate–drain voltage $V_{GD}$, comparable to the drain–source voltage $V_{DS}$, and maximum emission was obtained when $V_{GD} = V_{DS}/2$. Electrical measurements showed that the optical emissions result from the radiative recombination of electrons and holes near the junction. Similar experiments carried out by Meric et al [15] on single-layer graphene (SLG) devices have reported the formation of a p–n junction along the graphene channel. However, owing to the absence of the bandgap in SLG, the recombination of electrons and holes at/near the junction does not yield any radiation. In comparison, a bilayer graphene (BLG) device can serve as a prospective candidate in this regard since a bandgap can be opened and controlled simultaneously by application of an external electric field perpendicular to the layers. Thus, by creating a p–n junction along the bilayer channel by proper biasing of the device, we may be able to fabricate a novel source of terahertz radiation [16, 17] based on the recombination of carriers.

In this paper we show that the BLG device can change from unipolar state to ambipolar state by varying the drain–source bias along the bilayer channel at different top-gate voltages ($V_T$). This has been possible because of the very high gate capacitance of the top gate. We also report a quantitative analysis of the bandgap opening in the bilayer graphene energy spectrum. In order to control the gap and the position of the Fermi level independently, we have used the top- and back-gate device geometry. A solid polymer electrolyte and 300 nm thick SiO₂ were used as top-gate and back-gate materials, respectively. This top-gate arrangement allows us to shift the
Fermi energy significantly by applying a very small top-gate voltage (∼1 V) because of its higher gate capacitance due to the nanometer thick Debye layer [18]. In addition, our top-gate geometry is a very simple way as compared to depositing high κ dielectric electric materials like HfO 2 and Al 2 O 3 , using an atomic layer deposition technique. We determine the top-gate capacitance accurately by an application of top and back gates on a bilayer graphene device. It is shown that our device has a very high gate capacitance ∼1.5 μF cm⁻², which is nearly 125 times larger compared to the gate capacitance of 300 nm SiO 2 (12 nF cm⁻²).

2. Experiments and results

The device consists of a bilayer graphene flake prepared from micromechanical cleavage of highly oriented pyrolytic graphite (HOPG) and deposited on an Si/SiO 2 substrate with the oxide thickness (t) of 300 nm. The electrical contacts on the bilayer device were made by e-beam lithography, followed by thermal evaporation of 30 nm of gold and subsequent liftoff in acetone. The source–drain separation by thermal evaporation of 30 nm of gold and subsequent liftoff the bilayer device were made by e-beam lithography, followed graphite (HOPG) and deposited on an Si from micromechanical cleavage of highly oriented pyrolytic.

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2.1. Determination of polymer gate capacitance C T

Figure 2 shows the resistance of the channel as a function of V B for a fixed V T. For a given gate voltage V G:

\[ V_G = \frac{E_F}{e} + \phi = \frac{E_F}{e} + \frac{n e}{C_G} \tag{2} \]

where \( \frac{E_F}{e} \) is determined by the quantum capacitance of the bilayer and the potential \( \phi \) from the geometrical capacitance of the gate [18, 19]. In equation (2), for the top gate \( C_G = C_T \), \( V_G = V_T, n = n_T \); similarly for the back gate \( C_G = C_B \), \( V_G = V_B, n = n_B \). The gate-induced carrier density in a bilayer graphene is given by [24, 19]

\[ n = \alpha (\gamma_1 E_F + E_F^2), \quad E_F < \gamma_1 \tag{3} \]

where \( \gamma_1 \) is the inter-layer hopping energy (∼390 meV), \( \alpha = \frac{\gamma_1}{\gamma_1 + \gamma_2} \), and \( \nu_F \) is the Fermi velocity = 10⁶ m s⁻¹ [3]. Therefore, for a given \( V_T \), the induced carrier density in the bilayer sample is

\[ n_T = \alpha \left( \gamma_1 A + A^2 \right) = f(C_T, V_T) \tag{4} \]

where

\[ A = -\frac{1}{2} \left( \gamma_1 + \frac{C_T}{ae^2} \right) + \frac{1}{2} \left( \gamma_1 + \frac{C_T}{ae^2} \right)^2 + \frac{4C_T V_T}{ae}. \tag{5} \]

Similar expressions hold good for the back-gate geometry and when resistance is maximum (\( R_{\text{max}} \)) at a back-gate voltage \( V_B^{\text{max}} \), \( |n_T| = |n_B| \) to make the Fermi energy shift zero. Therefore, for a given \( V_T \)

\[ f(C_T, V_T) = f(C_B, V_B^{\text{max}}) \tag{6} \]
where $C_T$ is the only unknown parameter. Using the known $C_B = 12$ nF cm$^{-2}$ and $V_T^{\text{max}}$ for different $V_T$, the average value of $C_T$ is found to be $\sim 1.5 \mu$F cm$^{-2}$. Note that, in this estimation the quantum capacitance is not assumed to be a constant as was done by Meric et al [15]. Knowing $C_T$, $n_T$ is thus determined as a function of $V_T$ from equations (4) and (5). The experimental curve of figure 1(c) is then fitted to equation (1) giving $\mu = 730 \text{ cm}^2 \text{V}^{-1} \text{s}^{-1}$, $\delta n = 1.5 \times 10^{12} \text{ cm}^{-2}$ and $R_C = 150 \Omega$.

2.2. Formation of p–n junction along the bilayer channel

We now discuss the characteristics of drain–source current ($I_{DS}$) as a function of drain–source bias ($V_{DS}$). Figures 3(a) and (b) show $I_{DS}$ versus $V_{DS}$ for different top-gate voltages. The main noticeable feature is a clear nonlinear dependence of $I_{DS}$ on $V_{DS}$, and a significant effect of the gate voltage on the shape of the $I_{DS}$–$V_{DS}$ curves.

To understand the nonlinear $I_{DS}$–$V_{DS}$ curve, we look at the schematic in figure 4(a). For $V_{DS} \ll V_T$, the bilayer channel will be electron-doped for $(V_T - V_{D}^P) > 0$ and hole-doped for $(V_T - V_{D}^P) < 0$ and the doping ($n(x)$) will be homogeneous along the channel length. However, this is not the case when $V_{DS}$ is comparable to $V_T$. In this case the voltage difference between the gate and the bilayer channel varies from $(V_T - V_{D}^P)$ at the source to $V_{DS} - (V_T - V_{D}^P)$ at the drain electrode. Therefore, by varying the drain–source voltage ($V_{DS}$) at fixed $V_T$, the doping concentration $n(x)$ changes from n-type to p-type along the channel length. In figure 4(a), we have shown the carrier distribution $n(x)$, along the bilayer channel for three different cases of drain–source voltage ($V_{DS}$) at $(V_T - V_{D}^P) = 0.5 \text{ V}$.

**Case 1:** $V_{DS} < (V_T - V_{D}^P)$, and therefore the carriers $n(x)$ will be electrons in the bilayer channel with $n(x = 0) > n(x = L)$. In this region, $I_{DS}$ increases sublinearly with $V_{DS}$ because the average carrier concentration $\langle n(x) \rangle = \frac{1}{L} \int_0^L n(x) \, dx$ decreases with $V_{DS}$.

**Case 2:** $V_{DS} = (V_T - V_{D}^P)$, $n(x)$ will be zero at $x = L$ and therefore the conduction channel gets pinched off near the drain end, making the region devoid of charge carriers. At this point the slope of the $I_{DS}$ versus $V_{DS}$ curve undergoes a change (figure 4(b)).

**Case 3:** $V_{DS} > (V_T - V_{D}^P)$, the point in the channel where the pinch-off occurs, moves deeper into the channel drifting towards the source electrode. As $V_{DS} > (V_T - V_{D}^P)$, the gate is negatively biased with respect to drain near the drain region. As a result carrier concentration $n(x)$ will be holes near the drain region, as shown in the lowermost panel of figure 4(a). When $V_{DS}$ is increased beyond pinch-off, the current increases due to enhanced p channel conduction.

Thus the bilayer channel is now viewed as comprising of distinct electron and hole regions, with the electron-doped region shrinking as the applied drain–source bias is increased. The potential drop across the electron channel remains fixed at $V_T - V_{D}^P$ while the drop across the hole region (from drain end to pinch off) increases as $V_{DS} - (V_T - V_{D}^P)$, with the applied drain–source bias. As the device is operated beyond the pinch-off, the dominant current carrier changes from electron to holes.

![Figure 2](image1.png) Resistance versus back-gate voltage ($V_B$) for a fixed value of $V_T$.

![Figure 3](image2.png) (a) $I_{DS}$ versus $(V_{DS} - V_T^P)$ as a function of $V_T - V_T^P$ for $V_B = 0 \text{ V}$. (b) 3D plot showing the variation of $I_{DS}$ as function of both $T$ and $V_{DS}$. The point of inflection is shown by an arrow.
pinch-off starts appearing near the drain end and case 3: 
I shift towards the source end. (b) 
pinch-off at drain end.

A noticeable feature is the absence of current saturation in all the $I_{DS}$ versus $V_{DS}$ curves as compared to the monolayer case reported recently [15]. In order to address if the small length of the channel in our experiment (~500 nm) is responsible for non-saturation of current [15, 25], we carried out experiments on a device of drain–source separation ~2.5 μm and width ~1.5 μm. This also did not show any signature of current saturation.

In order to analyze the $I_{DS}$–$V_{DS}$ curves, we model the drain current as

$$I_{DS} = \frac{W}{L} \int_{0}^{L} e_{DS}(x) \sqrt{(\delta n)^2 + (\gamma \tau n(x))^2} \, dx \tag{7}$$

where $v_{DS}(x)$ is drift velocity. The drift velocity can be written as

$$v_{DS}(x) = \mu E(x) = \mu \frac{dV(x)}{dx} \tag{8}$$

Figure 4. (a) Schematic of the spatial profile of the carrier concentration ($n(x)$) along the channel for a particular top-gate voltage. Three cases are shown: case 1: ($V_{DS} \ll V_T - V_D^0$) when the carriers are only electrons; case 2: $V_{DS} = V_T - V_D^0$ when the pinch-off starts appearing near the drain end and case 3: $V_{DS} > V_T - V_D^0$ where the minimum carrier density point (pinch-off) shifts towards the source end. (b) $I_{DS}$–$V_{DS}$ curve for $V_T - V_D^0 = 0.5$ V pointing out the regions mentioned in (a). An inflection point appears at $V_{DS} = V_T - V_D^0 = 0.5$ V implying pinch-off at drain end.

Figure 5. Comparison between experiment (open circles) and theory (solid lines) done for three gate voltages.

where $E$ is the longitudinal electric field due to drain–source bias, $V(x)$ is the potential drop at point $x$ in the channel and $\mu$ is the mobility. Therefore

$$I_{DS} = \frac{W}{L} e\mu \int_{0}^{V_{DS}} \frac{\delta n}{R} \sqrt{(\delta n)^2 + (\gamma \tau n)^2} \, dV \tag{9}$$

where the upper and lower limits signify the voltage drop at the drain and source ends, respectively. The drop due to the contact resistance at both ends has been assumed to be equal. Using the extracted values of the mobility ($\mu$), the contact resistance ($R_C$), $\delta n$ and $\gamma \tau$, equation (9) is solved numerically. Figure 5 shows experimental data (open circles) for three top-gate voltages along with the theoretical curves (solid lines). It can be noted that agreement between the experiment and the calculation is quite good.

2.3. Opening of energy gap in bilayer graphene and its estimation

Coming back to figure 2, it shows resistance as a function of the back-gate voltage for a fixed top-gate voltage. For $V_T = 0$ V, the maximum value of resistance ($R_m$) at a negative back-gate voltage ($V_B = V_B^* \sim -40$ V) clearly establishes that the bilayer graphene channel is intrinsically n-doped. Figure 2 shows that the value of $R_m$ is minimum at $V_T = -0.4$ V and increases almost symmetrically on changing $V_T$. It can also be seen that, for a particular top gate voltage, the drain–source current is not symmetric for electron and hole doping.

The change in the maximum value of resistance ($R_m$) at different top-gate voltages arises due to the opening of an energy gap between the conduction and valence bands of the bilayer graphene [5, 10–13]. It has been shown both theoretically [6–8] and experimentally [5, 10–13] that a difference between the on-site energy in the layers leads to an opening of the gap between conduction and valence bands which touch each other at the zone edge K point of the Brillouin zone [8]. This on-site energy difference can be controlled externally by the application of an electric field,
perpendicular to the layers, which implies a potential energy difference \( \Delta V \) and hence a gap \( \Delta g \). Experimentally such fields in between two carbon layers were created either by application of top and bottom gates simultaneously [11–13] or by chemical doping of a back-gated device [5, 10]. In the presence of an electric field in between the layers, the Hamiltonian for the doping of a back-gated device \([5, 10]\). In the presence of an electric field in between the layers, the Hamiltonian for the bilayer graphene near the K point can be written as

\[
H = \begin{pmatrix}
-\frac{\Delta V}{2} & \gamma k & 0 & 0 \\
\gamma k & -\frac{\Delta V}{2} & \gamma_1 & 0 \\
0 & \gamma_1 & \frac{\Delta V}{2} & \gamma k \\
0 & 0 & \gamma k & \frac{\Delta V}{2}
\end{pmatrix}
\]  

(10)

where \( \gamma = \frac{\sqrt{3}}{2} \gamma_0 a \) where \( \gamma_0 \) and \( \gamma_1 \) are the in-plane and interlayer nearest-neighbor hopping energies, respectively. The eigenvalues of the above Hamiltonian for the lower subbands of the bilayer graphene can be written as

\[
e_\pm(k) = 
\pm \sqrt{\left(\frac{\Delta V}{4} + \frac{\gamma_1^2}{2} + \gamma_1^2 k^2\right)} - \sqrt{\left(\frac{\gamma_1^2}{4} + \gamma_1^2 k^2\right)^2 + (\Delta V)^2}
\]  

(11)

where \( \pm \) corresponds to conduction and valence bands, respectively. Figure 6(a) shows the band structure of bilayer graphene having a bandgap (\( \Delta g \)). The relation between the bandgap and potential energy difference (\( \Delta V \)) is given by [8]

\[
\Delta g = \frac{\gamma_1^2 (\Delta V)^2}{\gamma_1^2 + (\Delta V)^2}
\]  

(12)

which shows that there will be no bandgap if \( \Delta V = 0 \).

Figure 6(b) shows the induced carrier density in each carbon layer along with the electric field in between them in the presence of top and back gates. The total induced carrier density in the bilayer due to \( V_T \) is: \( n_T e = -C_T V_T \) and similarly, for \( V_B \), \( n_B e = -C_B V_B \). Therefore, the total induced carrier density in bilayer graphene due to top and back gates is

\[
n e = n_T e + n_B e = -[C_T V_T + C_B V_B]
\]  

(13)

where, for simplicity, we have neglected the quantum capacitance. Considering the screened electric field, the induced carrier density due to top gate is \( n_{T1} \) and \( n_{T2} \), where subscripts 1 and 2 refer to top and bottom layers, respectively, as shown in figure 6(b). For a screening length of \( \lambda \), we can write for the top gate \( n_{T1} = n_{T1} e^{-d/\lambda} \), where \( d \) is the separation between the two layers (3.41 Å). Thus, for the top gate \( n_{T1} = n_{T1} + n_{T2} \) and \( n_{T2} = \frac{n_T e}{\lambda} \). A similar expression holds good for the back gate. Thus, in the presence of back and top gates the resultant electric field inside the bilayer would be \( \tilde{E} = \tilde{E}_T + \tilde{E}_B \), where

\[
\tilde{E}_T = \frac{n_T e}{2e} - \frac{n_{T1} e}{2e} - \frac{n_{T2} e}{2e}
\]  

\[
= \frac{n_T e}{\epsilon} = \frac{C_T V_T}{\epsilon(1 + e^{d/\lambda})}
\]  

(14)

where \( \epsilon \approx 2.5 \) is the dielectric constant of the bilayer graphene [8].

The same analysis holds good for \( E_B \) as well. Therefore, the net electric field between two carbon layers is

\[
\tilde{E} = \tilde{E}_T + \tilde{E}_B,
\]

where

\[
E_T = \frac{n_T e}{2e} - \frac{n_{T1} e}{2e} - \frac{n_{T2} e}{2e}
\]  

\[
= \frac{n_T e}{\epsilon} = \frac{C_T V_T}{\epsilon(1 + e^{d/\lambda})}
\]

(15)

It should be noted that for \( \lambda = \infty \) equation (15) reduces to

\[
\tilde{E} = \frac{C_T V_T}{2e} - \frac{C_B V_B}{2e}
\]

(16)

i.e. the field without screening which corresponds to two layers having equal carrier density.

It can be seen from equations (13) and (15) that a minimal value of the resistance maximum should appear when \( V_B = 0 \) V and \( V_T = 0 \) V, since this would imply that Fermi energy \( E_F = 0 \) (since \( n = 0 \)) and bandgap \( \Delta g = 0 \) (since \( E = 0 \)). As mentioned earlier, in our experiment the minimum value of \( R_m \)
appears at $V_T = -0.4$ V (figure 2) because of unintentional electron doping. To consider the effect of electric field inside the bilayer due to this unintentional electron doping, we place a positive charge sheet of carrier density $n_0$ above the top carbon layer, given by $n_0 = C_B V_0'$ obtained from the back-gate sweep for $V_T = 0$ V, as shown in figure 2 ($V_0' \sim -40$ V). Thus the net electric field inside the bilayer is written as

$$\vec{E} = \vec{E}_T + \vec{E}_B + \vec{E}_0$$

where $\vec{E}_0$ is the field due to $n_0$. The potential energy difference between the two layers is $\Delta V = \epsilon(E \times d)$ and the value of the gap is estimated from equation (12). Taking backgate capacitance $C_B = 12$ nF cm$^{-2}$ and top-gate capacitance $C_T \approx 1.5$ $\mu$F cm$^{-2}$, figure 6(c) shows the plot of the value of the bandgap, with screening $\lambda = 5$ Å [3] and without screening $\lambda = \infty$, as a function of $V_T$ (where bandgap values are evaluated at $R_m$ for each of the back-gate characteristics at fixed $V_T$ (figure 2)). It can be seen from figure 6(c) that $\Delta g$ is a minimum at $V_T = -0.4$ V. This trend follows from the trend of $R_m$ (see figure 2). We notice that, had the arrangement of $n_0$ been placed below the bottom layer, then the field components associated with it would have changed their direction and the calculated energy gap would not have followed the trend of $R_m$. Thus, our assumption that the arrangement of unintentional carrier density $n_0$ lies above the top layer has indeed been justified.

### 3. Conclusions

In conclusion, the bilayer channel transforms from an n-type to p-type conduction channel as we vary the drain–source voltage. This variation results in a nonlinear dependence of $I_{DS}$ on $V_{DS}$ as a function of $V_T$ which has been quantitatively explained. Contrary to the recently reported monolayer case, we did not observe any signature of current saturation for $I_{DS}$. In the presence of a gap in the bilayer energy spectrum, the formation of p–n junction creates a new possibility for the bilayer device as a source of terahertz radiation [16, 17], similar to infrared emission from the carbon nanotubes [14]. The radiation from recombination between electrons and holes at the junction may act as a terahertz source, depending on the magnitude of the gap that can be opened. The opening of a gap in the bilayer spectrum was studied, where the gap was controlled using a top- and back-gate geometry. However, the bandgap opening is limited by the restriction on the back-gate voltage, since the breakdown field for the SiO$_2$ is $1$ V nm$^{-1}$ (up to $300$ V in our case). The capacitance of the polymer electrolyte was determined accurately. Thus the solid polymer electrolyte gating of graphene devices may open up new avenues for graphene-based electronics, particularly where higher carrier concentration is required.

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### References

[1] Novoselov K S, Geim A K, Morozov S V, Jiang D, Zhang Y, Dubonos S V, Grigorieva I V and Firsov A A 2004 Science 306 666--9
[2] Novoselov K S, Geim A K, Morozov S V, Jiang D, Katsnelson M I, Grigorieva I V, Dubonos S V and Firsov A A 2005 Nature 438 197--200
[3] Geim A K and Novoselov K S 2007 Nat. Mater. 6 183--91
[4] Bolotin K I, Sikes K J, Stormer H L and Kim P 2008 Phys. Rev. Lett. 101 096802
[5] Castro E V, Novoselov K S, Morozov S V, Peres N M R, Lopes dos Santos J M B, Nilsson J, Guinea F, Geim A K and Castro Neto A H 2007 Phys. Rev. Lett. 99 216802
[6] McCann E 2006 Phys. Rev. B 74 161403(R)
[7] McCann E and Falko V I 2006 Phys. Rev. Lett. 96 086805
[8] Castro E V, Novoselov K S, Morozov S V, Nilsson J, Guinea F, Geim A K and Castro Neto A H 2008 arXiv:0807.3348v1 [cond-mat]
[9] Gava P, Lazzerei M, Saitta A M and Mauri F 2009 arXiv:0902.4615v1 [cond-mat]
[10] Ohta T, Bostwick A, Seyller T, Horn K and Rotenberg E 2006 Science 313 951--4
[11] Ostinga J B, Heersche H B, Liu X and Morpugo A F 2008 Nat. Mater. 7 151--7
[12] Pal A N and Ghosh A 2009 Phys. Rev. Lett. 102 126805
[13] Zhang Y, Tang T, Girit C, Hao Z, Martin M C, Zettl A, Crommie M F, Shen Y R and Wang F 2009 Nature 459 820--3
[14] Misewich J A, Martel R, Avouris Ph, Tsang J C, Heinz S and Tersoff J 2003 Science 300 783--6
[15] Meric I, Han M Y, Young A F, Ozyilmaz B, Kim P and Shepard K L 2008 Nat. Nanotechnol. 3 654--9
[16] Berman O L, Gumbs G and Lozovik Y E 2008 Phys. Rev. B 78 085401
[17] Aleshkin V Y, Dubinov A A and Ryzhii V 2009 JETP Lett. 89 63--7
[18] Das A et al 2008 Nat. Nanotechnol. 3 210--5
[19] Das A, Chakraborty B, Pisana S, Piscanec S, Sood A K and Ferrari A C 2009 Phys. Rev. B 79 155417
[20] Das A, Sood A K, Govindaraj A, Saitta A M, Lazzeri M, Mauri F and Rao C N R 2007 Phys. Rev. Lett. 99 136803
[21] Ferrari A C et al 2006 Phys. Rev. Lett. 97 187401
[22] Adam S, Hwang E H, Galitski V M and Sharma S D 2007 Proc. Natl Acad. Sci. USA 104 18392--7
[23] Martin J, Akerman N, Ulbricht G, Lohmann T, Smet J H, von Klitzing K and Yacoby A 2008 Nat. Phys. 4 144--8
[24] Ando T 2007 J. Phys. Soc. Japan 76 104711
[25] Radosavljevic M, Heinze S, Tersoff J and Avouris Ph 2008 Appl. Phys. Lett. 83 2435--7