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Towards Graphene-Based Electronics

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13. SUPPLEMENTARY NOTES

14. ABSTRACT During the last year, we have published more than 20 research papers including 2 *Science* papers, 4 papers in *Nature Physics* and *Nature Communications* and 5 *Phys. Rev. Letters*. The most important technological result probably was the development of fabrication procedures to encapsulate graphene between boron-nitride crystals, which allows us to routinely achieve mobilities above 100,000 cm²/Vs and demonstrate room-temperature ballistic transport at micron scale (*Nano Lett.* **11**, 2396, 2011). This development also led to the first double-layer graphene heterostructures, in which we reported interesting interaction phenomena (*Nature Phys.* online 2011) and which continue to be in the focus of our attention offering a wealth of new physics and potential applications. Interaction phenomena have also been studied in suspended devices made from graphene and its bilayer (*Science* **333**, 860, 2011; *Nature Phys.* **7**, 701, 2011) and by using the nonlocal geometry (*Science* **332**, 328, 2011). As a result we can now routinely make and investigate complex graphene-BN heterostructures with mobilities 10 times higher than for graphene on the standard Si substrates. For suspended graphene devices, we achieve mobilities well above a million, that is, 100 times higher than for graphene on a Si substrate. Another important development over the last year was the demonstration of a graphene-based derivative, fluorographene that is a two-dimensional version of Teflon (*Small* **6**, 2877, 2010). In all these publications, the PIs have gratefully acknowledged the AFOSR support. As concerns the entire 3-year project, it resulted in 4 *Science* research papers and dozens of reports in *Nature* series magazines, *Phys. Rev. Letters*, *Nano Letters* and other high-quality research journals. Despite the short reported period, our research has already caused very high impact that can be quantified by the number of citations for the papers supported by the AFOSR grant. Two of them (*Science* 2009 and *Rev. Mod. Phys.* 2009) were cited >1,000 times, and another *Science* 2009 is rapidly approaching this threshold. Four other papers have already attracted more than 100 citations, and we are confident that no less than 20 research publications supported by this grant will eventually attract more than 100 citations. Our results were also presented in more than 100 invited talks, including approximately 20 named and plenary lectures. We were awarded the 2010 Nobel Prize in Physics, the 2010 Carty Award from the US National Academy of Sciences, and the 2009 Körber Prize.

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FINAL REPORT
Towards Graphene-Based Electronics
Grant FA8655-08-1-3088

Principal Investigators: *Professors Andre Geim and Kostya Novoselov*

The AFOSR BAA grant notably contributed to the rapid progress achieved in graphene research over the last 3 years and was essential in helping the PIs to keep ahead of ever increasing competition. Before summarizing the overall progress, let us describe the latest developments over the final year of Oct 2010 – Sept 2011 (details for previous years can be found in the corresponding annual reports).

During the last year, we have published more than 20 research papers including 2 *Science* papers, 4 papers in *Nature Physics* and *Nature Communications* and 5 *Phys. Rev. Letters*. The most important technological result probably was the development of fabrication procedures to encapsulate graphene between boron-nitride crystals, which allows us to routinely achieve mobilities above 100,000 cm²/Vs and demonstrate room-temperature ballistic transport at micron scale (*Nano Lett.* **11**, 2396, 2011). This development also led to the first double-layer graphene heterostructures, in which we reported interesting interaction phenomena (*Nature Phys.* online 2011) and which continue to be in the focus of our attention offering a wealth of new physics and potential applications. Interaction phenomena have also been studied in suspended devices made from graphene and its bilayer (*Science* **333**, 860, 2011; *Nature Phys.* **7**, 701, 2011) and by using the nonlocal geometry (*Science* **332**, 328, 2011). As a result we can now routinely make and investigate complex graphene-BN heterostructures with mobilities 10 times higher than for graphene on the standard Si substrates. For suspended graphene devices, we achieve mobilities well above a million, that is, 100 times higher than for graphene on a Si substrate. These recent developments are essential for improving the performance of graphene-based transistors and extending their frequency range. In addition, the high-quality heterostructures offer a possibility to proceed along several new venues towards graphene-based electronics such as, for example, vertical field-effect tunnelling transistors. Another important development over the last year was the demonstration of a graphene-based derivative, fluorographene that is a two-dimensional version of Teflon (*Small* **6**, 2877, 2010). In all these publications, the PIs have gratefully acknowledged the AFOSR support.

As concerns the entire 3-year project, it resulted in 4 *Science* research papers and dozens of reports in *Nature* series magazines, *Phys. Rev. Letters*, *Nano Letters* and other high-quality research journals. Despite the short reported period, our research has already caused very high impact that can be quantified by the number of citations for the papers supported by the AFOSR grant. Two of them (*Science* 2009 and *Rev. Mod. Phys.* 2009) were cited >1,000 times, and another *Science* 2009 is rapidly approaching this threshold. Four other papers have already attracted more than 100 citations, and we are confident that no less than 20 research publications supported by this grant will eventually attract more than 100 citations.

Our results were also presented in more than 100 invited talks, including approximately 20 named and plenary lectures. We were awarded the 2010 Nobel Prize in Physics, the 2010 Carty Award from the US National Academy of Sciences, the 2009 Körber Prize, several other prestigious international prizes as well as many distinctions such honorary fellowships and doctorates.

LIST OF PUBLICATIONS FOR THE FINAL YEAR (Oct 2010 – Sep 2011)

1. D. C. Elias, R. V. Gorbachev, A. S. Mayorov, S. V. Morozov, A. A. Zhukov, P. Blake, L. A. Ponomarenko, I. V. Grigorieva, K. S. Novoselov, F. Guinea, A. K. Geim. Dirac cones reshaped by interaction effects in suspended graphene. *Nature Phys.* **7**, 701-704 (2011).
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3. D. A. Abanin, R. V. Gorbachev, K. S. Novoselov, A. K. Geim, L. S. Levitov. Giant Spin-Hall Effect Induced by the Zeeman Interaction in Graphene. *Phys. Rev. Lett.* **107**, 096601 (2011).
4. A. S. Mayorov, D. C. Elias, M. Mucha-Kruczynski, R. V. Gorbachev, T. Tudorovskiy, A. Zhukov, S. V. Morozov, M. I. Katsnelson, V. I. Fal'ko, A. K. Geim, K. S. Novoselov. Interaction-Driven Spectrum Reconstruction in Bilayer Graphene. *Science* **333**, 860-863 (2011).
5. T. J. Echtermeyer, L. Britnell, P. K. Jasnós, A. Lombardo, R. V. Gorbachev, A. N. Grigorenko, A. K. Geim, A. C. Ferrari, K. S. Novoselov. Strong plasmonic enhancement of photovoltage in graphene. *Nature Commun.* **2**, 458 (2011).
6. A. S. Mayorov, R. V. Gorbachev, S. V. Morozov, L. Britnell, R. Jalil, L. A. Ponomarenko, P. Blake, K. S. Novoselov, K. Watanabe, T. Taniguchi, A. K. Geim. Micrometer-scale ballistic transport in encapsulated graphene at room temperature. *Nano Lett.* **11**, 2396-2399 (2011).
7. D. A. Abanin, S. V. Morozov, L. A. Ponomarenko, R. V. Gorbachev, A. S. Mayorov, M. I. Katsnelson, K. Watanabe, T. Taniguchi, K. S. Novoselov, L. S. Levitov, A. K. Geim. Giant nonlocality near the Dirac point in graphene. *Science* **332**, 328-330 (2011).
8. A. Luican, G. Li, A. Reina, J. Kong, R. R. Nair, K. S. Novoselov, A. K. Geim, E. Y. Andrei. Single-layer behavior and its breakdown in twisted graphene layers. *Phys. Rev. Lett.* **106**, 126802 (2011).
9. O. Frank, G. Tsoukleri, I. Riaz, K. Papagelis, J. Parthenios, A. C. Ferrari, A. K. Geim, K. S. Novoselov, C. Galiotis. Development of a universal stress sensor for graphene and carbon fibres. *Nature Commun.* **2**, 255 (2011).
10. F. Carbone, G. Aubeck, A. Cannizzo, F. van Mourik, R. R. Nair, A. K. Geim, K. S. Novoselov, M. Chergui. Femtosecond carrier dynamics in bulk graphite and graphene paper. *Chem. Phys. Lett.* **504**, 37-40 (2011).
11. R. V. Gorbachev, I. Riaz, R. R. Nair, R. Jalil, L. Britnell, B. D. Belle, E. W. Hill, K. S. Novoselov, K. Watanabe, T. Taniguchi, A. K. Geim, P. Blake. Hunting for monolayer boron nitride: optical and Raman signatures. *Small* **7**, 465-468 (2011).
12. E. V. Castro, H. Ochoa, M. I. Katsnelson, R. V. Gorbachev, D. C. Elias, K. S. Novoselov, A. K. Geim, F. Guinea. Limits on charge carrier mobility in suspended graphene due to flexural phonons. *Phys. Rev. Lett.* **105**, 266601 (2010).
13. R. Nair, W. Ren, R. Jalil, I. Riaz, V. Kravets, L. Britnell, P. Blake, F. Schedin, A. S. Mayorov, S. Yuan, M. I. Katsnelson, H. Cheng, W. Strupinski, L. G. Bulusheva, A. V. Okotrub, I. V. Grigorieva, A. N. Grigorenko, K. S. Novoselov, A. K. Geim. Fluorographene: A two-dimensional counterpart of Teflon. *Small* **6**, 2877-2884 (2010).
14. V. G. Kravets, G. Zoriniants, C. P. Burrows, F. Schedin, C. Casiraghi, P. Klar, A. K. Geim, W. L. Barnes, A. N. Grigorenko. Cascaded optical field enhancement in composite plasmonic nanostructures. *Phys. Rev. Lett.* **105**, 246806 (2010).
15. M. Sepioni, R. R. Nair, S. Rablen, J. Narayanan, F. Tuna, R. Winpenny, A. K. Geim, I. V. Grigorieva. Limits on Intrinsic Magnetism in Graphene. *Phys. Rev. Lett.* **105**, 207205 (2010).
16. R. R. Nair, P. Blake, J. R. Blake, R. Zan, S. Anissimova, U. Bangert, A. P. Golovanov, S. V. Morozov, A. K. Geim, K. S. Novoselov, T. Latychevskaya. Graphene as a transparent conductive support for studying biological molecules by transmission electron microscopy. *Appl. Phys. Lett.* **97**, 153102 (2010).
17. F. Schedin, E. Lidorikis, A. Lombardo, V. G. Kravets, A. K. Geim, A. N. Grigorenko, K. S. Novoselov, A. C. Ferrari. Surface-Enhanced Raman Spectroscopy of Graphene. *ACS NANO* **4**, 5617-5626 (2010).

ANNUAL REPORT 2010

Towards Graphene-Based Electronics

Grant FA8655-08-1-3088

Principal Investigators: *Professors Andre Geim and Kostya Novoselov*

The AFOSR BAA grant has significantly helped PIs in investigation of fundamental properties of graphene and its possible applications in electronics beyond the Si age, including the possibility of graphene-based ballistic transistors. Over the reported period of Oct 2009 – Sept 2010, the Manchester team has made significant progress in the understanding of the properties of graphene.

The most notable result has been the demonstration that by using strain it is possible to open significant band gaps and even achieve the quantum Hall effect without magnetic field (*Nature Phys.* 2010). Within a few months, this effect was confirmed experimentally by a Stanford group who reported pseudomagnetic fields up to 400 T and energy gaps $> 0.5\text{eV}$. In another set of work, PIs have demonstrated that so called resonant scatterers could be responsible for limiting carrier mobility in graphene (*Nano Lett.* 2010). This work continues, and we can now achieve mobilities over $100,000\text{ cm}^2/\text{Vs}$ for graphene encapsulated within boron-nitride. In such devices room-temperature mean free path reaches over $1\text{ }\mu\text{m}$ (unpublished). PIs has also measured quantum capacitance of graphene and demonstrated new devices with variable capacitance (Ponomarenko *et al*, *PRL* 2010). Measurements of graphene's magnetization revealed that graphene is diamagnetic and no sign of ferromagnetism was observed down to liquid helium temperatures, contrary to many artefacts reported in literature (Sepioni *et al*, *PRL* 2010).

Over the reported period, PIs have published 10 papers listed below, which acknowledged the AFOSR support. Our results were also presented in more than 40 invited talks, including 10 named and plenary lectures. In 2010, we were awarded the Nobel Prize in Physics and J. J. Carty Award from the US National Academy of Sciences.

1. F. Guinea, M. I. Katsnelson, A. K. Geim. Energy gaps and a zero-field quantum Hall effect in graphene by strain engineering. *Nature Phys.* **6**, 30-33 (2010).
2. F. Guinea, A. K. Geim, M. I. Katsnelson, K. S. Novoselov. Generating quantizing pseudomagnetic fields by bending graphene ribbons. *Phys. Rev. B* **81**, 035408 (2010).
3. Z. H. Ni, L. A. Ponomarenko, R. R. Nair, R. Yang, S. Anissimova, I. V. Grigorieva, F. Schedin, P. Blake, Z. X. Shen, E. H. Hill, K. S. Novoselov, A. K. Geim. On Resonant Scatterers As a Factor Limiting Carrier Mobility in Graphene. *Nano Lett.* **10**, 3868–3872 (2010).
4. L. A. Ponomarenko, R. Yang, R. V. Gorbachev, P. Blake, A. S. Mayorov, K. S. Novoselov, M. I. Katsnelson, A. K. Geim. Density of States and Zero Landau Level Probed through Capacitance of Graphene. *Phys. Rev. Lett.* **105**, 136801 (2010).
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6. A. J. M. Giesbers, U. Zeitler, L. A. Ponomarenko, R. Yang, K. S. Novoselov, A. K. Geim, J. C. Maan. Scaling of the quantum Hall plateau-plateau transition in graphene. *Phys. Rev. B* **80**, 241411 (2009).
7. S. Neubeck, L. A. Ponomarenko, F. Freitag, A. J. M. Giesbers, U. Zeitler, S. V. Morozov, P. Blake, A. K. Geim, K. S. Novoselov. From One Electron to One Hole: Quasiparticle Counting in Graphene Quantum Dots Determined by Electrochemical and Plasma Etching. *Small* **6**, 1469-1473 (2010).
8. S. Neubeck, Y. M. You, Z. H. Ni, P. Blake, Z. X. Shen, A. K. Geim, K. S. Novoselov. Direct determination of the crystallographic orientation of graphene edges by atomic resolution imaging. *Appl. Phys. Lett.* **97**, 053110 (2010).
9. R. R. Nair, P. Blake, J. R. Blake, R. Zan, S. Anissimova, U. Bangert, A. P. Golovanov, S. V. Morozov, A. K. Geim, K. S. Novoselov, T. Latychevskaia. Graphene as a transparent conductive support for studying biological molecules by transmission electron microscopy. *Appl. Phys. Lett.* **97**, 153102 (2010).
10. E. V. Kurganova, A. J. M. Giesbers, R. V. Gorbachev, A. K. Geim, K. S. Novoselov, J. C. Maan, U. Zeitler. Quantum Hall activation gaps in bilayer graphene. *Solid State Commun.* **150**, 2209-2211 (2010).

REPORT

Towards Graphene-Based Electronics

Grant FA8655-08-1-3088

Principal Investigators: *Professor Andre Geim* and *Dr Kostya Novoselov*

The AFOSR BAA grant has significantly helped PIs in investigation of fundamental properties of graphene and its possible applications in electronics beyond the Si age, including the possibility of graphene-based ballistic transistors.

Over the reported period of Oct 2008 – Sept 2009, the Manchester team has made significant progress in the understanding of the properties of graphene. By using graphene immersed in high- κ dielectrics, PIs have demonstrated that charged impurities can be contributing scatterers but do NOT limit graphene's mobility to currently achievable values of less than $20,000 \text{ cm}^2/\text{Vs}$ for graphene on a substrate (published in *Phys. Rev. Lett* 2009). The scattering mechanism has been investigated in several publications of PIs and, also, other groups addressed this problem but no clear picture has emerged yet.

Furthermore, PIs' team has investigated roughness of graphene membranes and demonstrated that nanoscale roughness is intrinsic, even if no adsorbates are present (*Nature Nanotechnology* 2008).

The most significant achievement over this period was the creation of graphane, a chemical derivative of graphene with one hydrogen atom attached to each carbon site (*Science* 2009). This new material is an insulator, which shows that the hydrogenation could be used to locally create semiconducting and insulating regions in all-graphene circuits. More generally, the work has demonstrated numerous opportunities that chemistry potentially offers for graphene research.

In 2009, PIs have published two reviews on graphene, in *Rev. Mod. Phys.* and in *Science*. Our results were also presented in more than 20 invited talks, including 5 named and plenary lectures.

Over the reported period, our work was acknowledged by the European Körber Prize, "Einstein Professorship" of the Chinese Academy of Sciences, and honorary doctorate from the Delft University (Netherlands).

PUBLICATIONS SUPPORTED BY THE AFOSR GRANT

1. P. Blake, R. Yang, S. V. Morozov, F. Schedin, L. A. Ponomarenko, A. A. Zhukov, I. V. Grigorieva, K. S. Novoselov, A. K. Geim. Influence of metal contacts and charge inhomogeneity on transport properties of graphene near the neutrality point. *Solid State Commun.* **149**, 1068-1071 (2009).
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4. D. C. Elias, R. R. Nair, T. M. G. Mohiuddin, S. V. Morozov, P. Blake, M. P. Halsall, A. C. Ferrari, D. W. Boukhvalov, M. I. Katsnelson, A. K. Geim, K. S. Novoselov. Control of graphene's properties by reversible hydrogenation: evidence for graphane. *Science* **323**, 610-613 (2009).
5. A. H. Castro Neto, F. Guinea, N. M. R. Peres, K. S. Novoselov, A. K. Geim. The electronic properties of graphene. *Rev. Mod. Phys.* **81**, 109-162 (2009).
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