A coustoelectric photoresponse of graphene nanoribbons

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Abstract
The acoustoelectric current in graphene nanoribbons, with widths ranging between 350 nm and 600 nm, has been investigated as a function of illumination. For all nanoribbon widths, the acoustoelectric current was observed to decrease on illumination, in contrast to the increase in acoustoelectric current measured in unpatterned graphene sheet devices. This is thought to be due to the higher initial conductivities of the nanoribbons compared to unpatterned devices.

Keywords: graphene, surface acoustic wave, nanoribbon, acoustoelectric

(Some figures may appear in colour only in the online journal)
2. Method

To study the AE photoresponse of GNRs monolayer graphene, grown by CVD on ~5 mm × ~5 mm copper foils (Graphene Supermarket), was transferred between the opposing interdigital transducers (IDTs) of a commercially available 128° YX LiNbO3 SAW delay line with a centre-to-centre IDT separation distance of 5.4 mm, and IDT aperture of 3.25 mm. The IDTs had a double-digit geometry, allowing the efficient excitation of SAWs at a number of resonant frequencies. The graphene was patterned into arrays of parallel nanoribbons with a 50% fill factor, using electron beam lithography and reactive ion etching, with the GNRs oriented such that their long-axis was parallel to the SAW propagation direction. Note that each array consists of many hundreds of nanoribbons, and that individual nanoribbons within an array are connected by a 500 nm-wide perpendicular bridge of graphene every 10 µm to help maintain electrical conductivity [33], as shown schematically in the magnified region of figure 1.

To enable the channel width dependence of the AE photoresponse to be studied, neighbouring arrays of GNRs with different nanoribbon widths were fabricated on the same SAW device, as shown schematically in figure 1. This device geometry enables a better comparison of the electronic properties of the GNR arrays, since each nanoribbon experiences the same SAW intensity and has undergone an identical fabrication process. Nanoribbon widths of 350, 400, 500 and 600 nm were characterised, with measured sheet resistances of 3.7, 3.8, 5.4, and 7.0 kΩ/□ respectively [31], so that the widest ribbons have the smallest electrical conductivity. Further details of the device layout and fabrication process can be found in [31].

All measurements were made under vacuum (chamber pressure approximately $6 \times 10^{-6}$ mbar) with continuous pumping to reduce the accumulation of dopants, at room temperature. Continuous wave SAWs were excited at the input transducer using a Hewlett-Packard 8648C RF signal generator, with the RF power set to +20.0 dBm. The AE current, $I_{ae}$, was measured using a Keithley K2400 source-measurement unit. Two-terminal current–voltage measurements were used to determine the GNR array conductivities, and arrays that were not being characterised were electrically grounded to reduce interference. The SAW amplitude at the output IDT was measured using a LeCroy WaveRunner 204Xi-A digital oscilloscope, and used to estimate SAW intensity.

A Thorlabs MCWHL2 LED (peak emission wavelength of 450 nm) was used to study the AE photoresponse. LED drive currents of 0.2 A and 1.4 A were used, producing an incident light intensity on the sample of 0.24 mW mm$^{-2}$ and 1.20 mW mm$^{-2}$ respectively after correcting for the measurement geometry. A motorised shutter was used to control the exposure of the sample to the LED.

3. Results and discussion

The measured AE current, for a nanoribbon width of 500 nm, is plotted as a function of time for SAW frequencies of 33 MHz and 355 MHz in figures 2(a) and (b) respectively. The vertical dashed lines indicate the time at which the motorised shutter was opened after 1 h, allowing illumination by the LED (with an intensity of 1.20 mW mm$^{-2}$) for a period of 1 h, before the shutter was then closed again. Although only results from 500 nm wide nanoribbons are presented here, similar results were obtained in all the nanoribbons. A negative current in the direction of SAW propagation was observed in all, corresponding to n-type doping of the nanoribbons, in contrast to the p-doping observed previously in these
nanoribbon arrays [31]. This most likely reflects the increased vacuum pump-out time before these new measurements were undertaken, leading to the removal of surface adsorbates that p-dope graphene, such as molecular water. The magnitude of the AE current was largest for a SAW frequency of 355 MHz in each nanoribbon array. This is thought to arise from an enhanced piezoelectric interaction between the GNRs and the SAWs when the SAW wavelength (approximately 11 μm at 355 MHz) is equal to the periodicity (10 μm) of the perpendicular graphene bridges in the array [31].

Upon illumination, a rapid decrease in the magnitude of the AE current was observed at both SAW frequencies in all GNR arrays. The fast initial change in the current is followed by a much slower decrease in current over the timescale of an hour or so. This effect was also observed in unpatterned graphene [22] and is broadly the same for different SAW frequencies. Unfortunately, the origin of this slow relaxation is unknown, and will be explored in future work. Closing the shutter again causes the current to quickly approach its original value. The decrease in the measured AE current under illumination contrasts with the AE photoresponse of continuous graphene sheets [22], where the magnitude of the current increased upon exposure to light. A larger change in AE current due to illumination was measured at the higher incident light intensity, and at the higher SAW frequency, as seen previously in graphene sheets. The conductivity of the GNRs (σ2D) was also recorded as a function of time and is plotted as the solid blue line in figure 2(c) for an illumination intensity of 1.20 mW mm−2. Upon exposure to the light, the conductivity quickly decreases, by as much as ~5% in the case of the array of 600 nm-wide GNRs. This compares to a decrease of up to 6% measured in the conductivity of an unpatterned graphene sample under the same illumination [22]. When the shutter is closed, the conductivity increases again towards its value prior to illumination.

The decrease in conductivity under illumination gives rise to an increase in the SAW attenuation per unit length, which can be calculated from the conductivity utilising the classical relaxation model widely used to describe the AE interaction between the SAWs and charge carriers in low dimensional systems [34, 35]:

$$\Gamma = \frac{K^2 \pi}{\lambda} \left[ \frac{(\sigma_{2D}/\sigma_M)}{1 + (\sigma_{2D}/\sigma_M)^2} \right]$$  \hspace{1cm} (1)

where $K^2$ is the piezoelectric coupling coefficient (0.056 in 128° YX LiNbO3), $\lambda$ is the SAW wavelength, and the attenuation is maximum at a characteristic conductivity, $\sigma_M$. In this work, a value of $\sigma_M = 10^{-7}$ Ω−1 was taken, which was extracted from previous measurements where we used an ion gel top gate [30] to modify the conductivity of unpatterned graphene on lithium niobate. The characteristic conductivity $\sigma_M$ was extracted from the measurement of SAW attenuation as a function of gate bias, with the value of $\sigma_M$ taken as the value of $\sigma_{2D}$ when the SAW attenuation was at a maximum (equation (1)). This value is likely to be sensitive to any non-uniformity of the graphene [30], and could vary from sample to sample due to differences in doping. However, as $\sigma_{2D}$ is much, much greater than $\sigma_M$, for all the ribbon widths and in unpatterned graphene, small variations in the characteristic conductivity are unlikely to alter the interpretation of the results obtained here. Future work will include the simultaneous measurement of the SAW attenuation, as a function of illumination, to probe this further.

The calculated attenuation coefficient is plotted for 500 nm ribbons in figure 2(c), showing how a decrease in conductivity under illumination leads to an increase in the attenuation coefficient. In figure 3(a) the decrease in measured conductivity under illumination, for intensities 0.24 mW mm−2 and 1.20 mW mm−2, is plotted as a function of time (solid blue line). The dashed red line shows the corresponding attenuation coefficient, which was calculated from the measured conductivity using equation (1).
occurs in the widest ribbons. We believe that this is because the widest ribbons have the smallest initial conductivity [31].

The AE current density, $j$, is determined both by the attenuation, but also by the charge carrier mobility $\mu$:

$$j = -\mu \frac{I}{v}$$  \hspace{1cm} (2)

where $I$ is the SAW intensity and $v$ is the velocity of the SAW (3979 m s$^{-1}$ in 128° YX LiNbO$_3$). In unpatterned graphene sheets, the increase in AE current under illumination was attributed to the generation of a hot carrier distribution [22]. Although this hot carrier distribution leads to a decrease in the charge carrier mobility $\mu$, the corresponding decrease in conductivity led to a much larger increase in the attenuation coefficient, due to the non-monotonic behaviour described by equation (1), resulting in an overall increase in the measured AE current.

The contrasting decrease of the measured AE current, under illumination, of the nanoribbons studied here is therefore likely due to the large difference in the initial conductivity of the unpatterned and nanoribbon graphene. The arrays of the 600 nm-wide and 350 nm-wide GNRs have conductivities $\sim 11 \times$ and $21 \times$ greater [31] respectively than that of a typical unpatterned device [20–22]. Therefore, a decrease in the conductivity of the nanoribbons under illumination leads to a smaller change in the attenuation coefficient than that seen in the continuous graphene. This is shown schematically in figure 4, where the calculated attenuation coefficient (equation (1)) is plotted as a function of $\left( \sigma^{2D} / \sigma_M \right)$. Under illumination, the conductivity of the nanoribbons decreases, but this only leads to a relatively small increase in the attenuation coefficient as compared to that observed in unpatterned graphene. This relatively small increase in the attenuation coefficient cannot therefore be large enough to compensate for the decrease in mobility, which overall leads to a decrease in the AE current under illumination.

4. Conclusion

In conclusion, we have investigated the AE current in arrays of monolayer CVD GNRs with widths in the range 350–600 nm, as a function of illumination. Under illumination, both the AE current and the conductivity were observed to decrease, where the decrease in conductivity is consistent with the generation of a hot carrier distribution [22]. Although this hot carrier distribution leads to a decrease in the charge carrier mobility $\mu$, the corresponding decrease in conductivity led to a much larger increase in the attenuation coefficient, due to the non-monotonic behaviour described by equation (1), resulting in an overall increase in the measured AE current.

The decrease of the measured AE current, under illumination, of the nanoribbons studied here is therefore likely due to the large difference in the initial conductivity of the unpatterned and nanoribbon graphene. The arrays of the 600 nm-wide and 350 nm-wide GNRs have conductivities $\sim 11 \times$ and $21 \times$ greater [31] respectively than...
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References
[1] Mas-Ballestre R, Gomez-Navarro C, Gomez-Herrero J and Zamora F 2011 2D materials: to graphene and beyond Nanoscale 3 20–30
[2] Rotter M, Wixforth A, Ruile W, Bernklau D and Riechert H 1998 Giant acoustic-electric effect in GaAs/LiNbO3 hybrids Appl. Phys. Lett. 73 2128–30
[3] Fal’ko V I, Meshkov S V and Iordanskii S V 1993 Acoustic-electric drag effect in the two-dimensional electron gas at strong magnetic field Phys. Rev. B 47 49910–2
[4] Shilton J M, Mace D R, Talyanskii V I, Galperin Y, Simmons M Y, Pepper M and Ritchie D A 1996 High-frequency single-electron transport in a quasi-one-dimensional GaAs channel induced by surface acoustic waves J. Phys.: Condens. Matter 8 L337–43
[5] Fletcher N E, Ebbecke J, Janssen T J B M, Ahlers F J, Pepper M, Beere H E and Ritchie D A 2003 Quantized acoustoelectric current transport through a static quantum dot using a surface acoustic wave Phys. Rev. B 68 245310
[6] Ford C J B 2017 Transporting and manipulating single electrons in surface-acoustic-wave minima Phys. Status Solidi b 254 1606586
[7] Barnes C H W, Shilton J M and Robinson A M 2000 Quantum computation using electrons trapped by surface acoustic waves Phys. Rev. B 62 8410–9
[8] Foden C L, Talyanskii V I, Milburn G J, Leadbeater M L and Pepper M 2000 High-frequency acoustoelectric-single-photon source Phys. Rev. A 62 011803
[9] Gumbs G and Abranyos Y 2004 Quantum entanglement for acoustic spintronics Phys. Rev. A 70 050302
[10] Giavaras G, Jefferyon J H, Ramšák A, Spiller T P and Lambert C J 2006 Quantum entanglement generation with surface acoustic waves Phys. Rev. B 74 195341
[11] Smith S J, Nash G R, Lewis M F, Bartlett C J, Buckley L, Emeny M T and Ashley T 2007 Acoustic charge transport in lateral n-i-p InSn/AlInAs—Sb quantum well diodes AIP Conf. Proc. 893 1111–2
[12] Couto O D D Jr, Lazić S, Ikawa F, Stotz J A H, Jahn U, Hey R and Santos P V 2009 Photon anti-bunching in acoustically pumped quantum dots Nat. Photon. 3 645–8
[13] Hermelin S, Takada S, Yamamoto M, Tarucha S, Wieck A D, Saminadayar L, Bauerle C and Meunier T 2011 Electrons surfing on a sound wave as a platform for quantum optics with Rydberg electrons Nature 477 435–8
[14] Miseikis V, Cunningham J E, Saeed K, O’Rorke R and Davies A G 2012 Acoustically induced current flow in graphene Appl. Phys. Lett. 100 133105
[15] Santos P V, Schumann T, Oliveira M H Jr, Lopes J M J and Riechert H 2013 Acousto-electric transport in epitaxial monolayer graphene on SiC Appl. Phys. Lett. 102 221907
[16] Roshchupkin D et al 2015 Surface acoustic wave propagation in graphene film J. Appl. Phys. 118 104901
[17] Hernandez-Miguez A, Tahraoui A, Lopes J M J and Santos P V 2016 Acoustoelectric transport at gigahertz frequencies in coated epitaxial graphene Appl. Phys. Lett. 108 193402
[18] Liu Y-T, Hernández-Miguez A, Herfort J, Lopes J M J, Tahraoui A and Santos P V 2017 Acousto-electric transport in MgO/ZnO-covered graphene on SiC J. Phys. D: Appl. Phys. 50 046408
[19] Preciado E et al 2015 Scalable fabrication of a hybrid field-effect and acousto-electric device by direct growth of monolayer MoS2/LiNbO3 Nat. Commun. 6 5893
[20] Bandhu L, Lawton L M and Nash G R 2013 Macroscopic acoustoelectric charge transport in graphene Appl. Phys. Lett. 103 133101
[21] Bandhu L and Nash G R 2014 Temperature dependence of the acoustoelectric current in graphene Appl. Phys. Lett. 105 263106
[22] Poole T, Bandhu L and Nash G R 2015 Acoustoelectric photoresponse in graphene Appl. Phys. Lett. 106 133107
[23] Insepov Z, Emelin E, Kononenko O, Roshchupkin D V, Tnyshytkybayev K B and Baigarin K A 2015 Surface acoustic wave amplification by direct current-voltage supplied to graphene film Appl. Phys. Lett. 106 023505
[24] Yurchenko S O, Komarov K A and Pustovoit V I 2015 Multilayer-graphene-based amplifier of surface acoustic waves AIP Adv. 5 057144
[25] Dompref K A, Mensah S Y, Abukari S S, Sam F and Mensah N G 2016 Amplification of acoustic waves in armchair graphene nanoribbon in the presence of external electric and magnetic fields Physica E 83 420–5
[26] Okuda S, Ikuta T, Kanai Y, Ono T, Ogawa S, Fujisawa D, Shimatani M, Inoue K, Maehashi K and Matsumoto K 2016 Acoustic carrier transportation induced by surface acoustic waves in graphene solution Appl. Phys. Express 9 045104
[27] Zheng S, Zhang H, Feng Z, Yu Y, Zhang R, Sun C, Liu J, Duan X, Pang W and Zhang D 2016 Acoustic charge transport induced by the surface acoustic wave in chemical doped graphene Appl. Phys. Lett. 109 183110
[28] Tang C-C, Chen Y-F, Ling D C, Chi C C and Chen J-C 2017 Ultra-low acoustoelectric attenuation in graphene J. Appl. Phys. 121 124505
[29] Liang J, Yang X, Zheng S, Sun C, Zhang M, Zhang H, Zhang D and Pung W 2017 Modulation of acousto-electric current using a hybrid on-chip AlN SAW/GFET device Appl. Phys. Lett. 110 243504
[30] Bandhu L and Nash G R 2016 Controlling the properties of surface acoustic waves using graphene Nano Res. 9 685–91
[31] Poole T and Nash G R 2017 Acoustoelectric current in graphene nanoribbons Sci. Rep. 7 1767
[32] Celis A, Nair M N, Tuleb-Ibrahimz A, Conrad A H, Kershaw Y and Santos P V 2016 Graphene nanoribbons: fabrication, properties and devices J. Phys. D: Appl. Phys. 49 143001
[33] Luxmoore I J, Gan C H, Liu P Q, Valmorra F, Li P, Faist J and Nash G R 2014 Strong coupling in the far-infrared between graphene plasmons and the surface optical phonons of silicon dioxide ACS Photonics 1 1151–5
[34] Wixforth A, Scriba J, Wassermeier M, Kothaas J P, Weimann G and Schlapp W 1989 Surface acoustic waves on GaAs/AlGaAs heterostructures Phys. Rev. B 40 7874–87
[35] Nash G R, Bending S J, Boero M, Grambow P, Eber K and Kershaw Y 1996 Anisotropic surface acoustic wave scattering in quantum-wire arrays Phys. Rev. B 54 R8337–40