interactions occurring within the specific phase of the polymer–nanotube complex. This approach could be relevant for the development of smart devices for *in situ* functional healing actions activated by a signal transmitted from a sensing element on selective responses to a metabolite. Despite recent advances[7], however, to become fully operational, smart devices based on carbon nanotube materials still need to overcome some limitations. Considering that the optoelectronic properties of the graphitic tubular framework are chirality-dependent, the main bottleneck for their use remains the unavailability of structurally and chirally homogeneous carbon nanotubes. Furthermore, strategies for wiring the sensing element to an operative unit also need to be developed. For example, functional groups introduced in several locations along the carbon nanotube (possibly including the inner cavity) could be used to confine pharmacologically active molecules to be released *in situ* when the recognition event occurs.

Carbon nanotube–polymer complexes such as those developed by Strano and co-workers are particularly amenable for achieving this level of structural complexity, because they allow integration of the polymeric unit with dynamic covalent[8] and non-covalent[9] linkages that are responsive to a stimulus[10]. Such developments take the field a step closer to the construction of multifunctional smart devices, such as those for *in situ* drug delivery. ❐

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NANOELECTROMECHANICAL SYSTEMS

Tuning in to a graphene oscillator

Self-sustaining electromechanical oscillators can be built from graphene membranes that vibrate at radiofrequencies and can be tuned by a gate voltage.

Philip X.-L. Feng

The sharp resonances of mechanical vibrations in solid-state structures make electromechanical resonators the elements of choice for frequency references in self-sustaining oscillators, which are used to generate, filter and mix signals in communication technologies. Self-sustaining oscillators can convert d.c. power into a.c. signals thanks to a positive feedback mechanism, which distinguishes them from passive resonators that require an external a.c. drive to maintain periodic vibrations. The frequency-determining electromechanical resonators, however, are usually off-chip bulky components such as quartz crystals. In recent decades, resonators made from micro- and nanoelectromechanical systems (MEMS and NEMS) have been developed as new frequency references for stable oscillators[1–3]. Of particular interest has been the development of

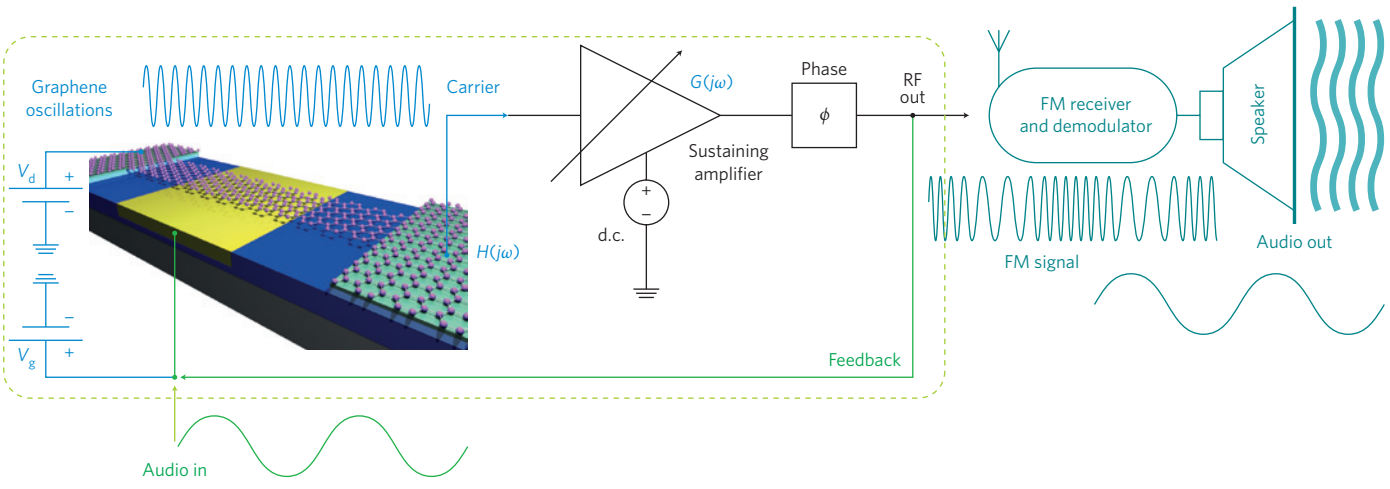

Figure 1 | A graphene NEMS self-sustaining oscillator as an FM radio station. The graphene NEMS resonator is configured in a vibrating channel transistor to efficiently transduce its motions into an electronic signal. The graphene vibrating transistor serves as a frequency-determining element, embedded in a positive feedback loop, thus creating a self-sustaining stable oscillator (the dashed-line box). Gate voltage can control the oscillation frequency, with broad frequency tunability. In one application, an audio signal modulates the graphene oscillator frequency and the output is received and demodulated by an FM receiver, demonstrating a prototype graphene FM radio station. Here V_g and V_d are gate and drain voltages, respectively; $H(j\omega)$ is the graphene NEMS frequency-response function and $G(j\omega)$ the feedback loop gain, both are complex variables including frequency-dependent amplitude and phase.

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oscillators based on NEMS resonators made from nanotubes[4], nanowires[5] or graphene[6], but various engineering challenges still need to be addressed with these emerging devices. Writing in *Nature Nanotechnology*, James Hone and colleagues at Columbia University now show that self-sustaining feedback oscillators can be created using graphene membrane resonators that can vibrate at radiofrequencies up to 110 MHz and can be electrostatically tuned by around 10%[7]. This is an important advance towards the development of voltage-controlled oscillators with very small on-chip footprints.

Graphene has a high elastic modulus ($E_Y \approx 1$ TPa) and a fracture strain limit of ~25%, which is orders of magnitude higher than that of the materials typically used to build MEMS and NEMS resonators[8]. These attributes, coupled with its excellent electronic properties, make graphene an attractive material for the development of tunable and stretchable two-dimensional NEMS that could be used in applications such as radiofrequency communications and sensing. Although a number of graphene NEMS resonators have previously been demonstrated[6,9], the construction of a self-sustaining, low-noise oscillator using a graphene resonator as the frequency reference has until now remained elusive. The major obstacles standing in the way of this goal have been the sensitive read out and then transduction into electrical signals of the small mechanical vibrations of graphene NEMS, as well as the further manipulation of these signals to control feedback circuitry.

Hone and colleagues used a 'vibrating channel transistor' scheme — a graphene field-effect transistor (FET) with a suspended channel that is free to move (Fig. 1) — to drive and sense the graphene vibrations. The application of a radiofrequency signal on a back gate produces an oscillating force between the gate and the graphene channel; sweeping the frequency of the gate excitation can identify the mechanical resonance of the graphene. At resonance, the charge density in the vibrating graphene channel is efficiently modulated, causing significant changes in the channel conductance, which is read out by measuring the oscillating current at the drain terminal of the transistor. Owing to the high electron mobility of graphene and the small air gaps attained in these devices (as small as 50 nm), strong electromechanical coupling is achieved, which efficiently transduces graphene NEMS resonant motions into electrical signals with high signal-to-background ratios of ~5 to 10 dB.

A strong resonance signal transduced from the vibrating graphene FET serves as a frequency-selecting element in the positive feedback circuitry of a self-sustaining oscillator. Calibration can then be performed to devise an electrical feedback to the graphene NEMS with the correct amplitude and phase to compensate its energy loss, so that the oscillations are sustained and stabilized. The team successfully implemented such positive feedback in their graphene NEMS oscillators. The feedback circuits they create are made from discrete components, but further engineering should enable on-chip integration of the graphene NEMS oscillators.

The self-sustaining feedback oscillators have advantages over existing passive graphene NEMS resonators. For example, Hone and colleagues observed a 72-fold linewidth compression and an effective quality factor Q of ~4,000 in the feedback oscillator at 52 MHz. This, in combination with the high responsivities of the graphene NEMS to external physical stimuli (temperature, force and surface adsorption of particles and molecules, for example), suggests that their devices could potentially be used in resonant sensing applications. The voltage-tuning capability of the frequency of the graphene NEMS voltage-controlled oscillators surpasses that of other electromechanical oscillators in MEMS and NEMS[7], which is promising for sensing with large dynamic ranges, and for tunable signal processing at ultralow power levels. Moreover, to illustrate the capabilities of their approach, the researchers created a graphene NEMS FM radio station (Fig. 1), using the device to transmit the song 'Gangnam Style' by PSY.

The full potential of graphene NEMS is yet to be realized. Even in the absence of external driving forces, graphene NEMS vibrate in resonant modes, due to the unavoidable thermal agitations at finite temperatures. Electrical detection of such thermomechanical vibrations is desirable, but challenging, and could be achieved by further development of ultrasensitive electronic displacement-sensing techniques. In the graphene oscillators developed by Hone and colleagues[7], the phase noise and dissipation processes are not as low as those in more mature oscillators. This is due to fluctuations in the electrical circuits, and to the electrostatic susceptibility of graphene to its surroundings. A trade-off exists between frequency stability and sensitivity to an external voltage, which makes the device tunable. There is, however, plenty of scope for improvement towards the fundamental limits of the material and device physics. In particular, the development of low-dissipative devices and ever quieter signal transduction schemes should further enhance the performance of self-sustaining, tunable oscillators based on graphene NEMS. ❐

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