Field Emission Applications of Graphene

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***Abstract*—Graphene has a huge variety of unique opto-electronic properties. Its recent rapid emergence and demonstrable richness in electron transport has been unprecedented. This atomically thin, ordered structure has exceptionally high attainable aspect ratios - potentially higher even than that of carbon nanotubes - whilst defective edge terminations rich in dangling bonds render it superior to metallic nanowires; qualifying graphene as a striking candidate for a variety of field emission applications following the addressing of various challenging fabrication issues. Herein we present a few potential uses of graphene in electron emission applications; specifically in micro-contact printing nanoscale fin electron sources, an edge-emission graphene-based video-rate display, and a highly electron transparent gate electrode capable of flat-band transparency and high beam collimation.**

Keywords—graphene; chemical vapour deposition; micro-printing; field emission; gate electrode; electron emisison display; electron transparency

I. INTRODUCTION

The graphitic allotropes have a proven potential in various field emission applications. The varied nanoscopic geometries of the structured graphites; the fullerenes, the nanotubes, and now graphene, all present high thermal and electrical conductivity, low sputter cross-sections, and low turn-on electric fields coupled to robustness towards high emission current densities, all of which have facilitated the development of a wide remit of novel electron sources. Graphene, a single atom thick two dimensional honeycomb of carbon atoms, has recently emerged as an interesting addition to the existing carbon portfolio and has already shown much promise, though the question remains; is the use of graphene – the very definition of a planar material – a wise idea in electron emission applications?

II. A MICRO-STRUCTURED GRAPHENE FIN ELETCRON SOURCE

Graphene grown by chemical vapour deposition (CVD) is now capable of producing individual monolayer grains a few millimeters in diameter. As such, extremely high field enhancement factors are clearly possible, making graphene an exciting material for field emission devices. Nevertheless, conventional processing is limited to producing films that lay flat on either the growth catalytic substrate or lying flat on arbitrary substrates following conventional polymer-mediated transfer. Nearest neighbour electrostatic shielding from the adjacent substrate prevents the fabrication of devices which realise the full morphological benefits of graphene. New fabrication techniques must therefore be developed to nanoengineer periodic structures capable of efficiently activating these high aspect ratio edges.

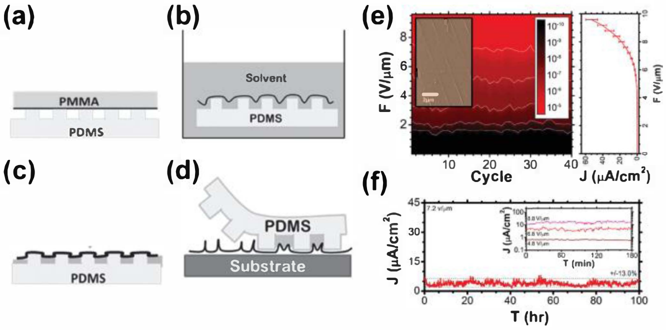

Fig 1. (a-d) Schematic depicting the bilayer graphene fin electron source fabrication procedure (scale bar: 2 μm). (e) Cyclic emission stability over 40 cycles and (right) the mean current density as a function of extraction field. Insert shows a scanning electron micrograph of a fabricated fin electron source. (f) Typical emission time stability profiles showing a mean variation in emission current density of ±13.0%. [1]

We have developed a micro-printing technique to controllably nanostructure CVD graphene into vertically standing fins [1]. This facile, large area compatible approach allows regular arrays of bilayer graphene fins to be formed, with sharp ridges that afford a new type of field emission electron source. Figure 2(a-d) outlines the fabrication process. Electrostatic simulations corroborated the measured field enhancement factor ($\beta \sim 445$) which was found to be consistent with the SEM observed topology. Raman analysis confirmed that the nascent high-quality monolayer graphene folds to form turbostratically aligned, vertically orientated bilayer fins. The emitters show surprising long-term (13.0%) and cyclic stabilities (Fig. 1(e,f)). The technique is highly tunable and can generate various pitches and aspect ratios.

Though micro-contact printing techniques such as this offer a commercially viable means to pattern large-area structured atomically thin fins the approach is limited in the attainable aspect ratios; the maximum strain graphene can accommodate is of the order of 25%. During solvent vaporisation, as the graphene conformally coats the master-stamp, the graphene is strained. This deleteriously shifts the work function and strain in excess of the failure strain leads to tears, thereby producing an upper bound on the realisable aspect ratio, with a corresponding field enhancement factor that is significantly less than the maximum attainable from a graphene monolayer ($\beta_{max} \sim 2x10^4$). Thus, to fully exploit the intrinsic high aspect ratio of monolayer graphene emitters must be engineered to lie vertically off of the adjacent supporting substrate which electrostatically shields these high-aspect ratio edges.

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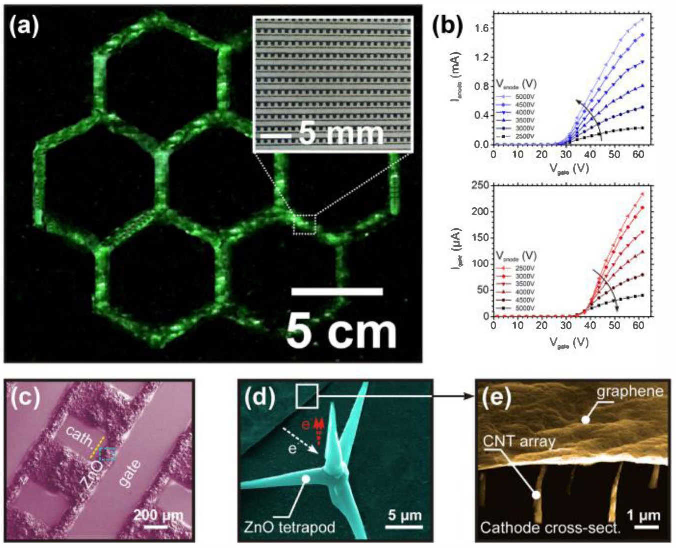

Fig 2. (a) Optical micrograph of a fabricated graphene-based electron emission display (scale bar: 5 cm). The insert shows an array of pixels (scale bar: 5 mm). (b) Anode and gate current dependence on the gate bias. Scanning electron micrographs of; (c) a pixel block (scale bar: 200 μm), (d) ZnO tetrapod gain media (scale bar: 5 μm), and (e) a section of the carbon nanofibre supported graphene edge emitter (scale bar: 1 μm).

III. GRAPHENE–BASED ELECTRON EMISSION DISPLAY

To mitigate substrate shielding we have developed an approach to lift the graphene off of the underlying substrate by supporting it on CVD vertically aligned carbon nanofibres, thereby allowing us to fabricated the first 21 cm diagonal graphene-based electron emission display (Fig. 2(a)). Each display pixel operates in a triode configuration with the planar gate and cathode formed from graphene. Given their high secondary electron yield, hydrothermally-synthesised ZnO tetrapods were deposited in the channel to function as a gain media which increased the anode current by 39.8% (V_{anode} = 5 kV). Figure 2(b,c,d) shows SEM micrographs of elements of a fabricated display. [2]

Though capable of video-rate imaging, graphene has a wide range of other unique properties and it's use in electron emission technologies may not necessarily be as electron source but rather as a next-generation gate electrode material.

IV. A GRAPHENE GATE ELECTRODE

Graphene is well-suited for applications requiring transparent conductive electrodes where a high transmission coefficient across a broad energy range is coupled too low sheet resistances, thereby ensuring negligible parasitic charging, low RC time constants, and high bandwidth pulsed operation. Here we report our work on developing a Mo/CVD graphene-based hybrid gate, as illustrated in Fig. 3(a).

In triode emitters we noted that the CVD graphene gates increased the electron transmission efficiency of the nascent metallic gate significantly (Fig. 3(b)), whilst integrated intensity maps showed that the angular dispersion of the transmitted beam was dramatically improved (87.9°) coupled with a 63% reduction in beam diameter (Fig. 3(c,d)). Impressive temporal stability was noted (<1.0%) with spatially resolved Raman analysis suggesting negligible damage to the graphene during long-term electron bombardment, likely due to the high knock-on threshold of *sp*^{2} carbon [3].

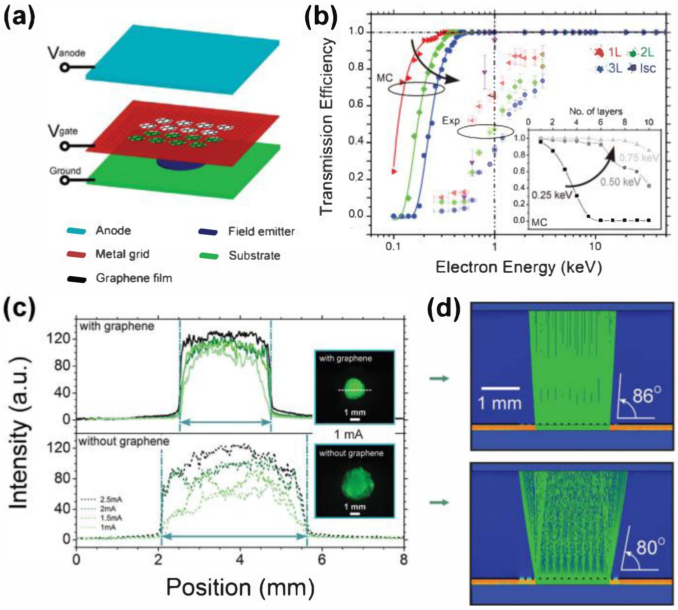

Fig 3. (a) Schematic depiction of the graphene gated triode. (b) Measured and simulated electron transparency of the CVD graphene. (c) Cross-sectional analysis of the far-field beam patterns. Insert: Optical micrograph of the emission profiles for gates with and without graphene (scale bar: 1 mm). (d) Simulated beam dispersion for emitters with (top) and without (bottom) graphene (scale bar: 1 mm).

V. CONCLUSION

Here we have summarised some emerging field emission applications of CVD graphene. To exploit graphene's unique morphological and electronic structure we have developed novel micro-structuring and elevated emission morphologies for the first edge-emission graphene-based display, in addition to an electron transparent gate electrode capable of supporting highly collimated emission.

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