Field Emission Applications of Graphene

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Electron Emission & the nanoCarbons

Electron emission is a ubiquitous technology. Found in traveling wave tubes, electron beam lithography systems, microwave amplifiers, thin film displays, advanced lighting units, and X-ray sources [1]; the field of nano-vacuum electronics is returning to the fore during the present carbon renaissance. The graphitic nano-carbons out-perform conventional metallic Spindt-like electron emitters across virtually all standardised metrics [2, 3]. Carbon nanotubes (CNT) and, more recently graphene both offer high-aspect ratios, chemical inertness, near instantaneous temporal response and low sputter cross-sections, all of which contribute to their advantageously low turn-on fields, negligible hysteresis and high temporal stability. Nevertheless, the efficient use of these emerging nanomaterials requires the ability to define, with high fidelity and reproducibility, sub-micron-scale periodic features. Though thought ill-suited for electron emission devices, due to its nominally planar nature, graphene has proven a rich platform on which to develop a number of unique electron emission systems. Here I present an over-view of our recent work on cheimical vapour deposited (CVD) graphene-based field electron emission devices, including; nanoscale graphene fin electron guns, low cost hydrogenated graphene foam electron emitters, highly electron transparent graphene gated triodes, and the first large-area graphene-based electron emission display.

Graphene Fin Electron Emitters

Carbon nanostructures have been much sought after for cold-cathode field emission applications. Herein a printing technique is reported to controllably nanostructure CVD graphene into vertically standing fins [4]. The method allows for the creation of regular arrays of bilayer graphene fins, with sharp ridges that, when printed onto gold electrodes, afford a new type of field emission electron source geometry. The approach affords tunable morphologies and excellent long term and cyclic stabilities.

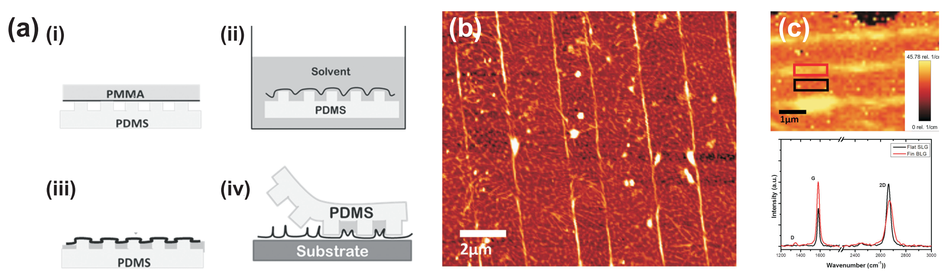


Figure 1. (a) Schematic for 3D graphene fi n printing. (b) A typical atomic force micrograph of a fabricated device. (c) Spatially resolved Raman map of the 2D peak FWHM and a typical Raman spectra for both fin (red) and flat (black) regions.

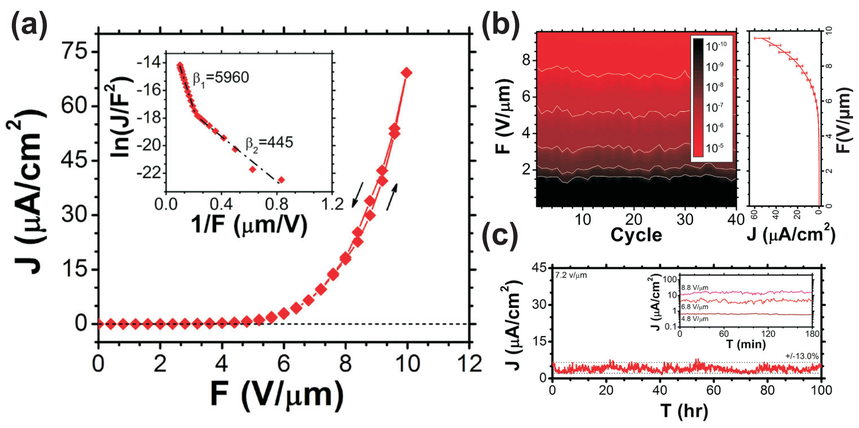


Figure 2. Field emission characteristics: (a) Emission current density (J) during one complete emission sweep and the corresponding Fowler–Nordheim plot. (b) Cyclic performance. Intensity denotes current density, J (A/cm^2). Right plot shows the mean emission current over 40 cycles. (c) Long-term (10 h) and short term (3 h, inset) temporal stability in emission current showing a typical variation of 13% at 7.2 V/ μm.

Hydrogenated Graphene Foam Electron Sources

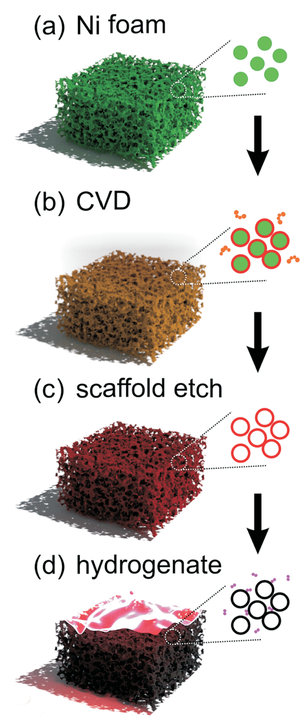


Figure 3. Synthesis of hydrogenated graphene foam.

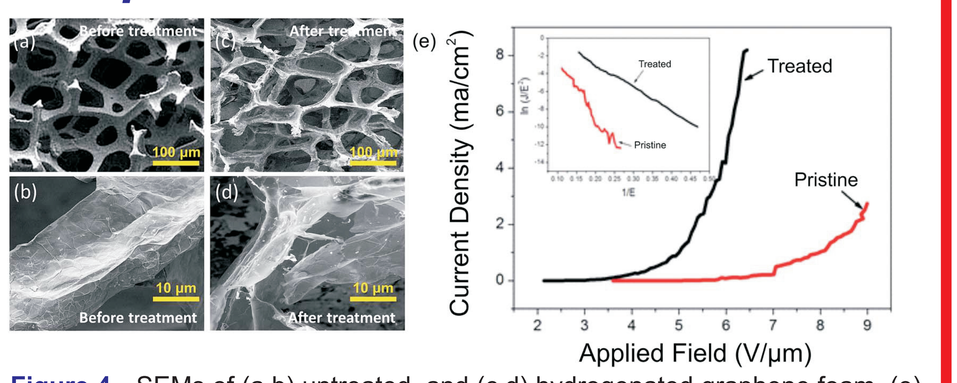


Figure 4. SEMs of (a,b) untreated, and (c,d) hydrogenated graphene foam. (e) Typical variation in current density as a function of the applied electric field (J–E). The insert depicts the corresponding Fowler–Nordheim.

The field emission performance of graphene foam (GF) is enhanced following transient exposure to hydrogen plasma [5]. The observed enhancement is attributed to an increase in the areal density of lattice defects and the formation of a partially hydrogenated, graphane-like material. The treated GF emitter demonstrated a much reduced macroscopic turn-on field (2.5 V/μm), with an increased maximum current density from 0.21 mA/cm^2 (pristine) to 8.27 mA/cm^2 (treated). The treated GFs vertically orientated protrusions, after plasma etching, effectively increased the local electric field resulting in a 2.2-fold reduction in the turn-on electric field. Further enhancement is attributed to hydrogenation and the subsequent formation of a partially hydrogenated structured 2D material, which advantageously shifts the emitter work function. Hydrogen plasma treatment increased the emission spatial uniformity, with an approximate four times reduction in the per unit area variation in emission current density. Our findings suggest that plasma treatments may provide an efficient, simple, and low cost means of realizing enhanced nanocarbon-based field emission devices.

A Graphene-based FED

The first graphene-based transverse field emission display (FED) panel has been developed [7]. Our 21 cm, screen-printed triode, edge emission geometry was realised using CVD graphene supported on vertically aligned CNTs. The CNT support minimize electrostatic shielding induced by the proximal substrate. Integrated ZnO tetrapod electron scatterers increase the emission efficiency by >90%. Simulated electron trajectories validate the observed emission characteristics with driving voltages less than 60 V. Fabricated display panels have shown real-time video capabilities that are hysteresis free (<0.2%), have extremely stable lifetimes (<3% variation over 10 h continuous operation) and a rapid temporal responses (<1 ms).

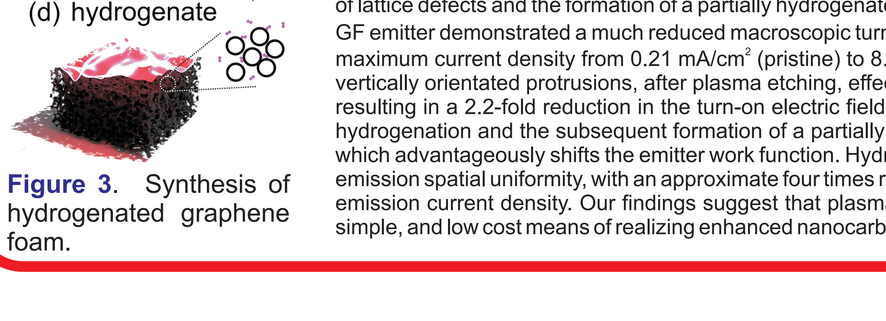


Figure 5. (a) Graphene edge FED fabrication. (b) Cross-section schematic. SEMs of (c) a single pixel, (d) a ZnO tetrapod amplifier, (e) the edge emission site and supporting CNTs. (f) Optical micrographs of a prototype 21 cm diagonal graphene FED and (inset) a 23 x 11 pixel section.

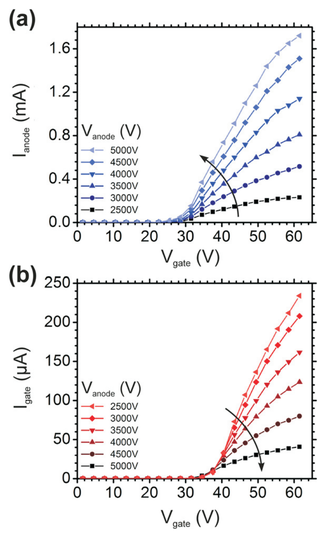
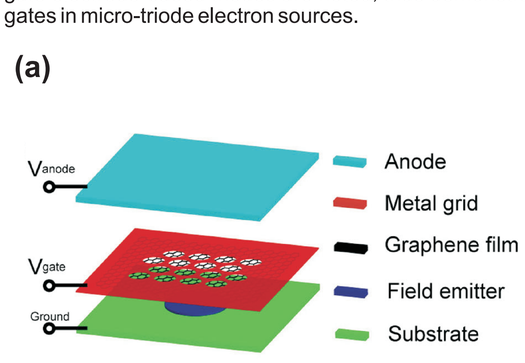


Figure 6. Modulated electron emission performance. (a) Anode current and (b) gate current as a function of gate and anode voltage.

Graphene Gate

The enhanced emission performance of a graphene/Mo hybrid gate electrode integrated into a nanocarbon field emission micro-triode electron source is presented [6]. Highly electron transparent gate electrodes are fabricated from chemical vapor deposited bilayer graphene transferred to Mo grids with experimental and simulated data, showing that liberated electrons efficiently traverse multi-layer graphene membranes with transparencies in excess of 50–68%. The graphene hybrid gates are shown to reduce the gate driving voltage by 1.1 kV, whilst increasing the electron transmission efficiency of the gate electrode significantly. Integrated intensity maps show that the electron beam angular dispersion is dramatically improved (87.9°) beam diameter. Impressive temporal stability is noted (<1.0%) with surprising negligible long-term damage to the graphene. A 34% increase in triode perveance and an amplification factor 7.6 times that of conventional refractory metal grid gate electrode-based triodes are noted, thus demonstrating the excellent stability and suitability of graphene gates in micro-triode electron sources.



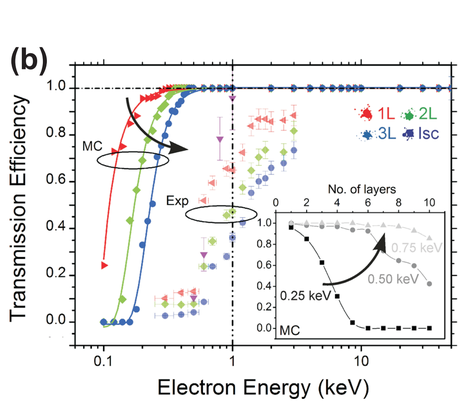


Figure 7. (a) Schematic of the graphene gate triode. (b) Simulated and measured electron transparency of chemical vapor deposited graphene.

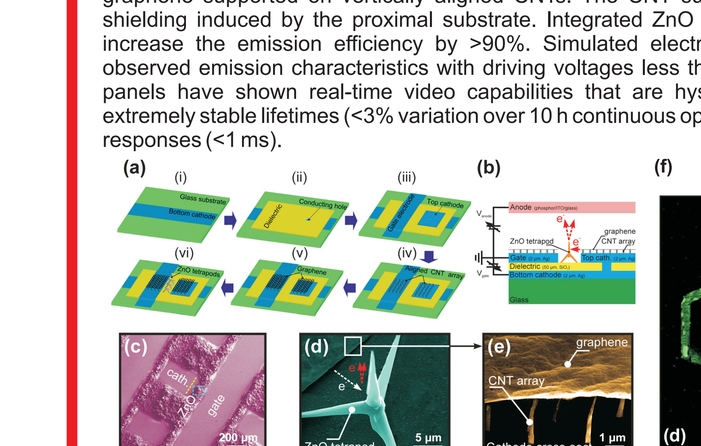


Figure 8. Electron beam spatial uniformity with and without graphene gating.

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