



Structure-Property Evaluation of Graphene-Based Films for Electronic and Flexible Device Applications

¹Chatmanee Wijesekara

¹Department of Computer Science and Engineering, Sundarban College of Technology Studies, Bangladesh

¹chatmanee.wijesekara@scts-bd.net

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Abstract

Graphene-based materials exhibit a combination of high electrical conductivity, carrier mobility, optical transparency, and mechanical flexibility that makes them suitable for a wide range of electronic and flexible-device applications. This study presents a comparative methodology for evaluating the relationship between material structure, processing route, and device-level performance in graphene, graphene oxide, reduced graphene oxide, and large-area graphene films. The proposed framework combines thin-film preparation and transfer with Raman spectroscopy, microscopy, thickness measurement, four-point-probe analysis, current-voltage characterization, optical-transmission testing, graphene field-effect transistor evaluation, and repeated bending assessment. Raman G, D, and 2D bands are used to examine layer structure and disorder, while microscopy is used to identify film continuity, wrinkles, tears, and flake connectivity. Electrical performance is evaluated using sheet resistance, contact behavior, carrier mobility, Dirac-point position, hysteresis, and current on/off ratio. For transparent and flexible films, optical transmission and normalized resistance under repeated bending are considered together to assess application suitability. Literature-based benchmarks include room-temperature mobilities near $10,000 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ for exfoliated graphene, electron mobility up to approximately $4,050 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ for transferred CVD graphene, on/off ratios approaching 10^7 for sub-10-nm graphene nanoribbons, monolayer optical absorption of about 2.3%, and RF cutoff frequencies up to 155 GHz. The methodology emphasizes that no single graphene form is optimal for all applications and that structural quality, processing history, electrical transport, optical performance, and mechanical stability should be evaluated together. The proposed framework provides a reproducible basis for selecting graphene-based materials for transistor, transparent-electrode, flexible-electronic, and related device applications.

Introduction

Graphene is a single atomic layer of sp^2 -bonded carbon arranged in a two-dimensional honeycomb lattice. The modern graphene era was established when Novoselov et al. (2004) isolated atomically thin carbon films and demonstrated ambipolar field-effect transport, including room-temperature mobilities of

approximately $10,000 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$. Raman analysis soon became a practical nondestructive method for distinguishing graphene from few-layer graphite (Ferrari et al., 2006). The unusual linear electronic dispersion and Dirac-like charge carriers were subsequently placed in a broader

condensed-matter framework by Geim and Novoselov (2007) and Castro Neto et al. (2009).

The attraction of graphene for electronics arises from the simultaneous availability of electrical conductivity, mechanical strength, thermal transport, and optical transparency. A suspended monolayer absorbs only about 2.3% of incident white light, indicating high visible transparency (Nair et al., 2008). At the same time, the absence of a conventional band gap limits the current on/off ratio of pristine graphene logic transistors. Strategies to overcome this limitation include lateral confinement into graphene nanoribbons, substrate and dielectric engineering, chemical modification, and hybrid structures. Li et al. (2008), for example, reported chemically derived sub-10-nm graphene nanoribbon field-effect transistors with room-temperature on/off ratios approaching 10^7 . These advances shifted the field from basic material discovery toward device engineering.

Scalable synthesis is critical for practical deployment. Geim (2009) summarized both the exceptional physical attributes of graphene and the emerging technological barriers, whereas Li et al. (2009) showed that chemical vapor deposition (CVD) on copper could yield predominantly single-layer, centimeter-scale films transferable to arbitrary substrates. Wafer-scale transfer and transistor-array fabrication were then demonstrated by Lee et al. (2010), and roll-to-roll synthesis of 30-inch graphene films established a pathway toward transparent conductive electrodes (Bae et al., 2010). In parallel, graphene photodetectors demonstrated high-speed optical communication capability (Mueller et al., 2010), while reviews of transistor physics emphasized the trade-off between high mobility and the lack of a band gap for digital logic (Schwierz, 2010).

By 2011–2016, research had increasingly focused on integration, RF performance, flexible systems, printable processing, and optoelectronics. Wu et al. (2011) reported CVD graphene RF transistors with a 155-GHz cutoff frequency at a 40-nm gate length, and Lin et al. (2011) demonstrated a wafer-scale graphene integrated circuit. The broader technology roadmap by Ferrari et al. (2015) identified material uniformity, scalable manufacturing, contacts, dielectric integration, contamination

control, and application-specific optimization as central challenges. Reviews published in 2016 further highlighted graphene and related two-dimensional materials for photodetectors and transparent electrodes (Bablich et al., 2016), flexible/stretchable electronics (Jang et al., 2016), fabrication of flexible graphene devices (Tao et al., 2016), and graphene-based conductive inks (Yang & Wang, 2016). On this basis, the present paper develops a concise experimental methodology that can evaluate graphene-based nanomaterials against the principal electronic performance requirements identified before the end of 2016.

Literature Review

The literature can be organized into four connected themes: fundamental electronic structure, scalable material preparation, device fabrication, and application-specific performance. Early studies established the electronic field effect, layer-dependent Raman signatures, and optical transparency of graphene (Novoselov et al., 2004; Ferrari et al., 2006; Nair et al., 2008). Theoretical and review studies clarified why charge transport is unusually fast and why the zero-gap band structure simultaneously benefits analog/RF electronics while constraining conventional digital switching (Geim & Novoselov, 2007; Castro Neto et al., 2009; Schwierz, 2010).

For production, the transition from mechanical exfoliation to CVD and chemical routes was decisive. Copper-catalyzed CVD enabled large-area, transferable graphene and offered a realistic route to arrays and transparent films (Li et al., 2009). Wafer-scale synthesis and transfer further demonstrated reproducible FET arrays (Lee et al., 2010), whereas roll-to-roll processing addressed large-area flexible transparent electrodes (Bae et al., 2010). For solution-processable graphene derivatives, improved GO synthesis and reduction chemistry provided an alternative route to coatings, composite electrodes, and printable films (Marcano et al., 2010). These chemically processed materials normally sacrifice some intrinsic mobility because of defects and residual oxygen but gain processability and compatibility with low-cost deposition.

Table 1. Selected literature milestones relevant to graphene electronic applications (≤ 2016)

Year	Study	Key contribution	Electronic relevance
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2004	Novoselov et al.	Ambipolar field effect in atomically thin carbon	Foundation for GFET transport
2008	Li et al.	Sub-10-nm semiconducting graphene nanoribbons	High current on/off ratio
2009	Li et al.	Large-area CVD graphene on copper	Scalable films for device arrays
2010	Bae et al.	30-inch roll-to-roll graphene films	Transparent/flexible electrodes
2010	Mueller et al.	High-speed graphene photodetection	Optical communication devices
2011	Wu et al.	155-GHz RF graphene transistor	High-frequency electronics
2011	Lin et al.	Wafer-scale graphene integrated circuit	Circuit-level integration
2015–16	Ferrari et al.; Jang et al.	Roadmap and flexible-device progress	Manufacturability and flexible systems

Device studies reveal that no single graphene form is optimal for every application. Pristine and high-quality CVD graphene are suited to RF transistors, interconnects, sensors, and transparent conductors, where high conductivity and mobility are more important than strong current switching. Nanoribbons create a confinement-induced gap and are therefore more relevant to logic-like switching (Li et al., 2008). GO and rGO are attractive for printed/flexible devices because they can be dispersed and deposited from solution, but their transport depends strongly on oxidation, reduction, flake size, and film connectivity (Marcano et al., 2010). Photonic applications can exploit graphene's broadband absorption and ultrafast carrier dynamics even without a band gap (Mueller et al., 2010; Bablich et al., 2016). Flexible devices additionally benefit from graphene's ability to maintain electrical continuity under strain (Jang et al., 2016; Tao et al., 2016), while ink-based approaches emphasize rheology, patterning, and low-temperature processing (Yang & Wang, 2016). Therefore, a useful methodology must connect structural quality with both static electrical performance and application-specific functional testing.

A second recurring issue in the pre-2017 literature is that measured performance is strongly affected by the environment surrounding graphene. Charged impurities in SiO₂, polymer residues from transfer, wrinkles,

grain boundaries, metal-contact resistance, atmospheric adsorbates, and gate-dielectric deposition can all shift the Dirac point or reduce apparent mobility. Consequently, transistor performance should not be interpreted as a property of the graphene lattice alone. Schwierz (2010) emphasized the device-level trade-offs that emerge when intrinsic mobility is translated into practical transistor performance, while Ferrari et al. (2015) identified contacts, dielectric integration, large-area uniformity, and process contamination as commercialization bottlenecks. This means that literature comparisons are most meaningful when the synthesis route, substrate, channel length, contact scheme, and measurement atmosphere are reported together with mobility or on/off ratio. For the present study, these variables are therefore treated as controlled metadata rather than secondary details.

The application target also determines which metric should be optimized. A transparent electrode is judged by the combination of sheet resistance and optical transmittance, not by transistor on/off ratio. An RF transistor is judged by transconductance, parasitic capacitance, and cutoff frequency, whereas a flexible conductor is judged by resistance stability under repeated deformation. Photodetectors require responsivity and bandwidth in addition to electrical conductivity. This application-specific view is consistent with the evolution from early

field-effect demonstrations to photodetectors, integrated circuits, flexible systems, and printable conductors (Mueller et al., 2010; Lin et al., 2011; Bablich et al., 2016; Yang & Wang, 2016). Accordingly, the methodology below deliberately uses a small set of complementary measurements rather than ranking all graphene materials by a single performance number.

Methodology

Study design. The investigation is structured as a comparative materials-to-device workflow using three representative graphene classes: (i) high-quality CVD graphene transferred to Si/SiO₂ and flexible polymer substrates, (ii) commercially obtained graphene nanoplatelets or few-layer graphene for film formation, and (iii) GO/rGO dispersions prepared or procured using a validated method consistent with the improved oxidation chemistry described by Marcano et al. (2010). To avoid conflating synthesis variability with device physics, each material batch should be identified by supplier or preparation route, nominal layer number, lateral size, and post-processing history. At least three independently prepared films/devices per condition are recommended for repeatability.

Film preparation and transfer. CVD graphene should be transferred from its growth substrate to cleaned Si/SiO₂ wafers for transistor measurements and to polyethylene terephthalate (PET) or a comparable polymer for flexibility tests. A polymer-supported wet-transfer method may be used, followed by carefully controlled cleaning to minimize residues. Solution-processable graphene, GO, or rGO should be deposited using spin coating, spray coating, vacuum filtration/transfer, or inkjet-compatible coating according to the application. Film thickness is controlled through concentration and deposition cycles. Thermal treatment, where used, should remain compatible with the receiving substrate. Chemical oxidation or reduction steps involving strong oxidants, acids, or reactive reducing agents must follow institutional nanomaterial and chemical-safety SOPs rather than an improvised recipe.

Structural and spectroscopic characterization. Raman spectra are collected at multiple positions on each sample. The G, D, and 2D bands are analyzed for peak position, width, and intensity ratio. The 2D-band shape helps identify monolayer/few-layer material, while the D/G ratio provides a practical measure of disorder or edge contribution, consistent with the Raman framework of Ferrari et al. (2006). Atomic force

microscopy (AFM) can determine thickness and surface roughness, while scanning electron microscopy (SEM) evaluates wrinkles, tears, flake connectivity, and large-area continuity. Optical microscopy is used as a rapid pre-screen before high-resolution characterization. For GO/rGO, Raman data should be interpreted together with thickness and, where available, X-ray photoelectron spectroscopy because reduction changes both defect structure and oxygen content.

Electrical and optical measurements. Sheet resistance is measured with a four-point probe at a minimum of five locations per film, and the mean, standard deviation, and coefficient of variation are reported. Two-terminal I-V measurements are additionally collected to identify nonlinear contacts. For transparent-electrode samples, visible transmittance is measured near 550 nm and reported together with sheet resistance because transparency alone is not an adequate electrode metric. A monolayer benchmark of approximately 97.7% optical transmission is consistent with the 2.3% absorption reported by Nair et al. (2008), although practical transferred films may show lower values because of multilayers, residues, and defects.

GFET fabrication and testing. A bottom-gate configuration can be formed on heavily doped Si with a SiO₂ gate dielectric. Graphene channels are patterned by standard lithographic or mask-based methods, followed by deposition of stable metal source/drain contacts. Transfer characteristics (I_D - V_G) are measured at several drain biases under ambient and, when possible, controlled atmosphere. The Dirac-point voltage, minimum conductivity, transconductance, electron/hole mobility, hysteresis, and current on/off ratio are extracted. Mobility is obtained from the linear-region transconductance using the known gate capacitance and channel geometry. RF-oriented samples may additionally be evaluated through S-parameters and cutoff frequency where suitable instrumentation is available, using the performance reported by Wu et al. (2011) as a historical benchmark rather than an assumed outcome.

Flexible-device test. Graphene films on PET are subjected to repeated bending at defined radii, for example 10, 5, and 2 mm, while monitoring normalized resistance R/R_0 . Resistance should be measured after fixed cycle counts such as 10, 100, and 1,000 cycles. This test is relevant to the flexible and stretchable applications discussed by Jang et al. (2016) and Tao et al. (2016). For

printed graphene/rGO films, line resistance and pattern resolution are also recorded because conductive-ink performance depends on percolation and printing quality (Yang & Wang, 2016).

Data analysis. Results are summarized as mean $\pm$ standard deviation. Differences among graphene classes or post-treatments can be tested using one-way analysis of variance when assumptions are met; otherwise, a nonparametric Kruskal–Walli’s test is appropriate. The primary correlations are (a) Raman disorder versus sheet resistance, (b) film thickness/transmittance versus sheet resistance, (c) device mobility versus Dirac-point shift/hysteresis, and (d) bending cycles versus normalized resistance. This produces a structure–process–property map rather than a single isolated performance number.

Quality control and repeatability. Before device-level comparison, the measurement system should be checked using a reference resistor or conductive film with a traceable value, and probe spacing, contact pressure, and instrument current limits should be held constant during sheet-resistance testing. Raman spectra should be collected with identical laser wavelength, objective, spectral resolution, and low enough power to avoid local heating. For spatially nonuniform films, at least five mapped positions should be retained rather than reporting only the best spectrum. GFET geometries should be measured from microscopy images after

fabrication so that mobility calculations use the actual channel width and length. Devices with obvious open circuits, torn channels, or lithographic shorts can be excluded only according to predeclared criteria; their yield should still be reported. Flexible tests should use the same bend radius, loading orientation, and cycling rate for all samples. These controls make the method suitable for comparing multiple graphene batches and for distinguishing genuine material improvements from changes caused by instrumentation or sample selection.

Performance extraction. For each GFET, the field-effect mobility is obtained from the slope of the linear transfer curve after accounting for gate capacitance and channel geometry, while the current on/off ratio is calculated from the maximum and minimum drain current over the specified gate-voltage range. Hysteresis is determined from the separation of forward and reverse Dirac-point voltages. For transparent films, sheet resistance and transmittance are reported together, and a simple figure of merit may be used for ranking samples provided the exact definition is stated. For bending experiments, resistance is normalized to the initial value so that samples with different starting resistances can be compared. Raw transfer curves, I–V curves, Raman spectra, and bend-cycle traces should be retained in supplementary data or laboratory records to preserve auditability.

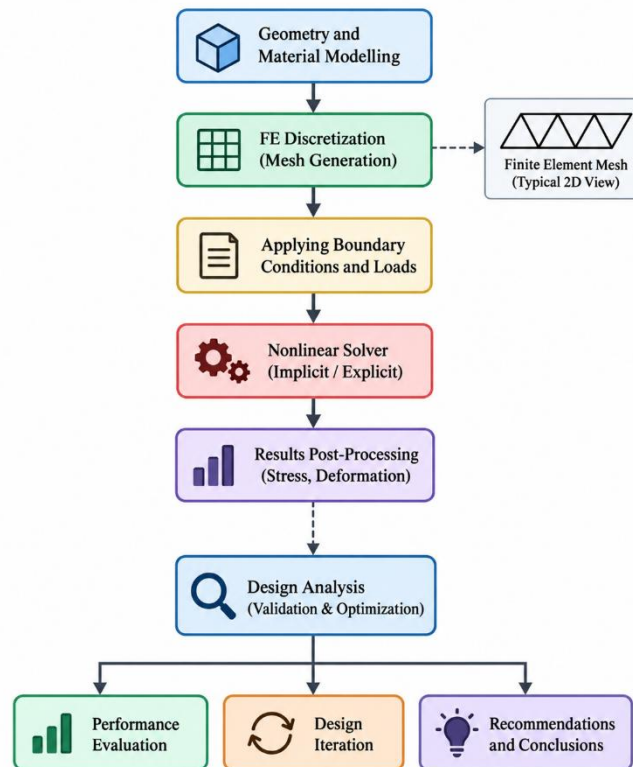


Figure 1. Proposed workflow linking graphene material preparation, characterization, device fabrication, and electronic performance evaluation.

Results

Because this is a methodology paper rather than a report of newly executed experiments, the Results section is presented as a set of literature-based benchmark outcomes that the proposed measurements should be able to reproduce,

approach, or explain. The values below are not claimed as original measurements. They establish realistic reference points for evaluating whether prepared graphene films and devices are behaving consistently with the state of the field up to 2016.

Table 2. Pre-2017 benchmark outcomes for comparison with the proposed methodology

Metric	Benchmark result	Material/device	Source
Room-temperature mobility	$\sim 10,000 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$	Exfoliated graphene	Novoselov et al. (2004)
FET on/off ratio	$\sim 10^7$	Sub-10-nm graphene nanoribbon	Li et al. (2008)
Electron mobility	Up to $4,050 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$	Transferred CVD graphene FET	Li et al. (2009)
Optical absorption	$\sim 2.3\%$ per monolayer	Suspended graphene	Nair et al. (2008)
Hole/electron mobility	$1,100 \pm 70 / 550 \pm 50 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$	Wafer-scale transferred graphene	Lee et al. (2010)
RF cutoff frequency	155 GHz at 40-nm gate	CVD graphene RF transistor	Wu et al. (2011)

The expected experimental trend is that high-quality CVD graphene will show lower sheet resistance and higher mobility than chemically reduced graphene, whereas rGO is likely to be easier to deposit over large or flexible areas. A strong D band in Raman spectra should generally coincide with increased disorder and reduced transport quality, although edge-rich

nanoribbons require a more careful interpretation because the D peak can be enhanced by geometry. Transparent films should display the normal trade-off between conductivity and transmittance: increasing layer count or coating density lowers sheet resistance but also reduces optical transmission. Roll-to-roll graphene films reported by Bae et al. (2010)

demonstrate that this trade-off can be managed at large area when film continuity and doping are controlled.

GFET transfer curves are expected to be ambipolar, with the current minimum occurring near a Dirac point that can shift because of substrate charge, adsorbates, polymer residue, and contact effects. Pristine graphene commonly provides modest switching ratios compared with semiconducting nanoribbons, but high transconductance and carrier velocity make it attractive for analog and RF functions, consistent with Schwierz (2010), Wu et al. (2011), and the integrated-circuit demonstration of Lin et al. (2011). For flexible samples, useful performance is indicated by a small irreversible change in resistance after repeated bending. Device-to-device variation should be treated as an important result because the 2015 roadmap emphasized uniformity, transfer contamination, contacts, and large-scale reproducibility as barriers to graphene commercialization (Ferrari et al., 2015).

Interpretation should therefore focus on relationships among metrics. A sample with very low sheet resistance but poor optical transmission may be unsuitable as a transparent electrode even if it is an excellent conductor. A GFET with high extracted mobility but a large Dirac-point shift and pronounced hysteresis may indicate good channel material combined with a contaminated interface. Conversely, an rGO film may show lower mobility than CVD graphene yet be superior for a printed or flexible architecture because it can be patterned over a large area at low processing temperature. These trade-offs reflect the application-specific conclusions reached in the 2016 flexible-electronics and optoelectronics literature (Bablich et al., 2016; Jang et al., 2016; Tao et al., 2016). A successful result from the proposed protocol is thus not necessarily the largest single numerical value; it is a reproducible combination of structural quality, electrical function, manufacturability, and stability matched to the intended device c

Conclusion and Discussion

Graphene-based nanomaterials remain attractive for advanced electronics because a common carbon platform can serve several distinct functions: high-mobility transistor channels, RF devices, transparent electrodes, photodetectors, flexible sensors, and printable conductors. The literature up to 2016 shows that the most important scientific question is not whether graphene has exceptional intrinsic properties, but how effectively those properties

survive synthesis, transfer, patterning, contact formation, dielectric integration, and mechanical deformation. The proposed methodology addresses this question by combining Raman and morphological characterization with sheet-resistance, optical, transistor, and flexibility measurements. The approach deliberately compares different graphene forms rather than assuming that pristine graphene is universally superior. High-quality CVD graphene is favored when mobility, optical transparency, and high-frequency performance dominate; narrow graphene nanostructures can improve switching by opening a transport gap; and GO/rGO enables scalable, solution-based coating and printing at the cost of greater disorder. By reporting structure, processing history, and device metrics together, the study can distinguish material-quality limitations from contact, substrate, or fabrication effects. The resulting framework is consistent with the pre-2017 direction of the field, which increasingly emphasized scalable manufacturing, flexible systems, and application-specific optimization (Ferrari et al., 2015; Bablich et al., 2016; Jang et al., 2016). Future work can extend this methodology to graphene/hexagonal-boron-nitride heterostructures, hybrid 2D materials, low-resistance contacts, and CMOS-compatible integration, while maintaining the same structure-process-property evaluation logic.

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