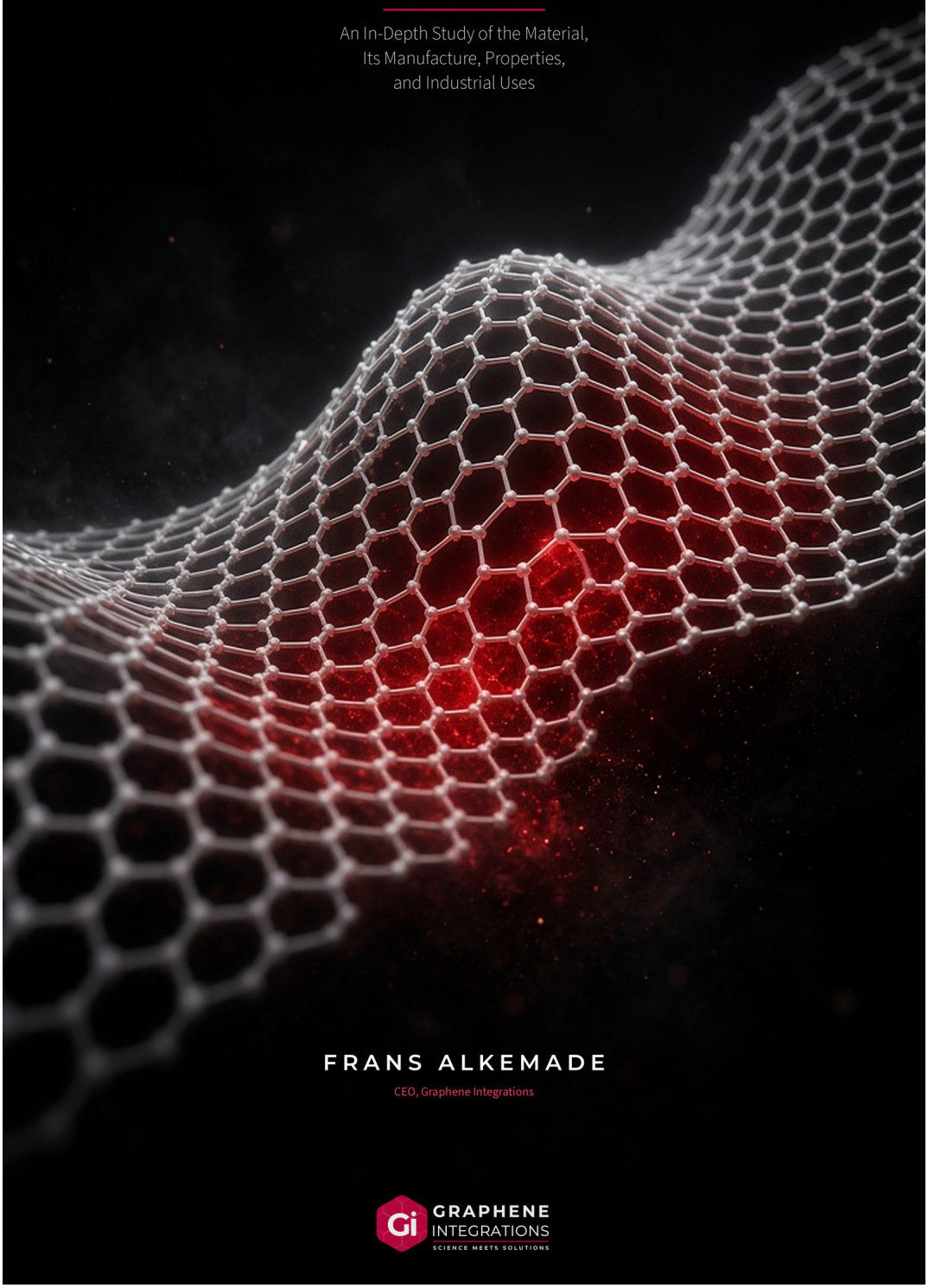
GRAPHENE

An In-Depth Study of the Material,
Its Manufacture, Properties,
and Industrial Uses



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GRAPHENE INTEGRATIONS
SCIENCE MEETS SOLUTIONS

GRAPHENE

An In-Depth Study of the Material, Its Manufacture, Properties and Industrial Uses

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Charlotte, NC area

https://grapheneintegrations.com

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Preface



Frans Alkemade, CEO of Graphene Integrations (Charlotte, NC area).

The first thing Dr. Arthur L. Schawlow put in my hand was not a paper or a prize citation. It was a roll of wintergreen Life Savers.

Stanford's physics labs smelled of warm electronics and ambition. Lasers glowed behind doors where grown-ups spoke the language of spectroscopy and light. A Bay Area kid tagging along on those visits could not have named the equations on the chalkboards, but the feeling stuck. Science was something you could walk into. Someone important enough to run a laboratory still had time for candy, and that small kindness made the whole place feel less like a temple and more like an invitation.

That path into science began before memory could keep it. Holland was home at the start. When I was one year old, my family crossed to America and settled in California's Bay Area so my father could work in Stanford's physics department alongside Dr. Schawlow. Schawlow shared the 1981 Nobel Prize in Physics for contributions to the development of laser spectroscopy. As our family tells it, he credited my father for help with that work. That credit is a family account, held with quiet pride, not a claim on the official citation.

The bond did not stop at the lab door. Years later, Dr. Schawlow came to my wedding. Between Life Savers on childhood visits and his presence on my wedding day, a scientist who helped shape the modern laser became part of a personal story that pulled me toward materials science and, much later, toward graphene. My respect for careful measurement, and for the people who do the unseen work behind a breakthrough, started there.

High tech came first. As Director of Apple iMac Operations, I sat in rooms with Steve Jobs: hard meetings, clear expectations, products that had to ship. A castle dinner in South Korea put Tim Cook and the CEO of LG Electronics at the same table, an evening that still reminds me how global supply chains are built one relationship at a time. Moving iMac production to China was the kind of operational bet that shows up on a balance sheet. By my account, it saved more than $750 million in manufacturing at a time when Apple had about $3 billion in the bank. Terry Gou, CEO of Hon Hai (Foxconn), told me the

work had impressed him enough to appear in his personal memoirs. Whether or not that line ever reaches print, the lesson was unmistakable.

Great materials and great ideas only matter when they can be made at scale: on time, at cost, with partners who can deliver. Laboratories invent. Factories decide what the world actually gets.

That discipline came with me when I moved to the Carolinas in 2008. Curiosity about graphene, the atom-thick carbon sheet that had leapt from theory into industrial conversation, grew into a company. Graphene Integrations took shape in the Charlotte, NC area, with our sister company Nano Technology Chemicals (NTC) as a chemical distributor and toll blender. Our work is exfoliation, dispersion, and putting graphene into concrete, lubricants, coolants, coatings and composites in forms that plants can actually use. The manufacturing experience from Apple did not disappear. It became the filter for every claim we are willing to put on a label.

When people hear “graphene”, two stories usually arrive together. One is the laboratory story: a material one atom thick that conducts heat and electricity extraordinarily well and opened the field of two-dimensional materials. The other is the marketplace story: enthusiasm, confusion about product grades, and a smaller set of uses that have truly moved into plants and products.

This book is for the people who make decisions in the gap between those stories: engineers, buyers, formulators, and readers who want the science without the mythology. It covers the history that got us here, the properties that matter in real formulations, the manufacturing routes that produce very different materials under one word, and a plain look at safety and markets. The final chapter describes how Graphene Integrations approaches the work. Our claims are limited to what we can stand behind, with the test context stated. Our process recipes stay confidential. Field performance still has to be proven in your system.

Better questions are the goal. What grade? How many layers? How is it dispersed? What was the control? What does the SDS say? If this book makes those questions easier to ask, and harder to dodge, it has done its job.

Frans Alkemade CEO, Graphene Integrations Charlotte, NC area

How to Use This Book

Structure. Chapters 1 to 3 cover history, what graphene is and how it is made. Chapters 4 to 8 cover thermal, electrical, mechanical, barrier and optical properties, each moving from the ideal single sheet to the real bulk material. Chapters 9 and 10 cover dispersion, integration and applications by industry. Chapter 11 covers safety, health, environment and standards; Chapter 12 the market; and Chapter 13 how Graphene Integrations works. The appendices contain a practical toolkit (templates and worked calculations), reference data tables and a glossary.

Reading paths.

- *Engineers:* Chapters 2 and 3, then the property chapter that matches your problem. Read Chapter 9 before trusting any bulk claim, then Chapters 10 and 11.
- *Buyers and formulators:* Chapters 2, 3, 9 and 12, and Appendix A.
- *General readers:* Chapters 1, 2 and 12, and the Glossary.

Three kinds of evidence. The book separates three kinds of statement. Results from peer-reviewed literature are cited by number. Graphene Integrations' published product results are labeled as such, with their test context: third-party, independent laboratory, or internal. Questions that remain open are identified as open. No studies, numbers or quotations have been invented.

References. Numbered citations in square brackets refer to the References section near the end of the book, in order of first citation. Journal articles include their DOI (Digital Object Identifier), a permanent link of the form https://doi.org/10..., which leads to the exact article. Company web pages are identified as company pages; they are not peer-reviewed.

Figures. Diagrams were drawn for this book from the published data or equations cited in their captions. Curves labeled "calculated" are computed from the stated model and are illustrations, not measurements. No journal figures have been reproduced.

Worked examples. Several chapters include short calculations, such as the Kapitza resistance of an interface, the Nielsen barrier model and the shear-lag length of a flake. They show how the numbers behave and are not design values.

Chapter 1. History: From Graphite Theory to the Nobel Prize

On Friday evenings in Manchester, Andre Geim's laboratory made room for experiments outside its main line of work. One of them asked a question that sounded almost naive: how thin could graphite be made before it stopped behaving like graphite? Adhesive tape lifted flakes from crystals. Oxidized silicon wafers turned thickness into color. Lithography turned the thinnest flakes into devices. The sheets survived ambient air, they conducted, and a gate voltage could swing their charge carriers from electrons to holes. When *Science* published that work in October 2004, graphene entered physics as a measured material rather than a theoretical idealization [1–3].

The road to those experiments was long. It ran through pencil mines and acid flasks, a 1947 band calculation, chemists who oxidized graphite into yellow-brown solids, a naming convention that took decades to settle, buckyballs and nanotubes, a levitating frog, and a rejection letter. This chapter tells that story for a practical reason. Later chapters will meet coolant loops, concrete cylinders and lubricant tests that claim "graphene," and the claims can only be read properly against the experiments that made the word famous.

1.1 Carbon that writes, lubricates, and refuses to be only one thing

Every pencil line is evidence of layered carbon. Graphite consists of flat sheets of carbon atoms bonded strongly within each plane and only weakly between planes. Pressed against paper, the sheets shear apart and leave a gray trail, while each individual sheet stays intact. The same element bonded tetrahedrally in three dimensions gives diamond its hardness. Curved into closed cages or rolled into tubes, the hexagonal sheet becomes a fullerene or a nanotube. Graphene, in the strict laboratory sense, is a single one of those hexagonal sheets standing alone: one atom thick, a honeycomb of sp^2-bonded carbon [4, 5].

Industry used layered carbon for centuries before anyone could isolate a single plane. Graphite lubricated machinery, lined crucibles, moderated nuclear reactors and filled pencils. Its geology and the weak van der Waals forces between its planes are still the starting point for most graphene powders and dispersions sold today (Chapter 3). What changed, slowly, was the ambition to treat one plane as a material in its own right, together with the vocabulary needed to stop monolayer, few-layer, oxide and nanoplatelet from collapsing into one marketing word. That vocabulary is the subject of Chapter 2 and of the international standard ISO/TS 80004-13 [6, 7].

1.2 Oxidizing the stack: Brodie, Hummers and Boehm

In 1859, the Oxford chemist Benjamin Brodie was trying to determine the atomic weight of graphite. He treated graphite repeatedly with potassium chlorate and fuming nitric acid, and obtained a light-colored, oxygen-rich solid that could be dispersed in water [8]. Later generations called it graphite oxide. Brodie's route was slow and hazardous. Nearly a century later, William Hummers and Richard Offeman

published a faster method in a one-page 1958 paper, using potassium permanganate and sodium nitrate in concentrated sulfuric acid [9]. “Hummers’ method” and its many modified versions remain the most common source of graphene oxide. In 2010, a group at Rice University reported an improved version that omits sodium nitrate, uses more permanganate and adds phosphoric acid. It gives more oxidized material, avoids the toxic gas generated by the original method, and makes temperature easier to control [10].

Graphite oxide was not graphene. It was a chemical door into the spaces between graphite’s layers, which could then be prised apart in water. In 1962, Hanns-Peter Boehm and colleagues chemically reduced dispersed graphite oxide and studied the resulting carbon films by electron microscopy. They reported extremely thin carbon foils, some of which they judged to be single layers [11]. Their measurements could not establish the electronic quality of those sheets, and the material was chemically modified. Geim’s Nobel lecture nonetheless credits Boehm’s generation with seeing thin carbon long before 2004 [2].

The word itself came from nomenclature work. In 1986, Boehm, Setton and Stumpp proposed “graphene” as the name for a single carbon layer of the graphite structure, in recommendations on graphite intercalation compounds [12]. IUPAC adopted the term in its 1994 recommendations [13]. The suffix “-ene” signaled a polycyclic aromatic structure, like naphthalene or anthracene, extended without limit.

1.3 Wallace’s 1947 calculation: electrons before devices

In May 1947, *Physical Review* published “The Band Theory of Graphite” by Philip Wallace, a Canadian physicist then working at the National Research Council’s laboratory at Chalk River. Wallace used the tight-binding approximation to calculate the electronic energy bands of the hexagonal lattice. He concluded that graphite is “a semi-conductor with zero activation energy”: with no free electrons at absolute zero, but with carriers created at higher temperatures by excitation into a band touching the filled one. He estimated that conductivity parallel to the planes is about 100 times greater than across them [4].

Wallace was studying graphite, not isolating graphene, and he had no reason to treat a single layer as a physical object. Yet his calculation started from one layer, and it contains the result that made graphene famous six decades later. Near the corners of the hexagonal Brillouin zone (the points now labeled K and K′), the conduction and valence bands of a single layer meet at a point, and energy rises linearly with momentum. Electrons there behave as if they had no mass. Chapter 2 explains that physics. When Manchester measured graphene’s ambipolar field effect in 2004, the surprise was not unusual electrons in theory. It was that a sheet could be made, contacted, gated, and trusted in air [1, 14].

1.4 Could a true two-dimensional crystal even exist?

For decades, theory gave physicists reasons to doubt that a free-standing two-dimensional crystal could exist. In 1968, N. David Mermin proved that thermal fluctuations destroy conventional long-range crystalline order in two dimensions for a broad class of interaction potentials [15]. Related arguments by

Peierls and Landau pointed the same way. Thin films were known to become unstable as thickness fell, tending to break up into islands or decompose. Popular retellings compressed these results into “2D materials are impossible.”

The reality is more nuanced, and the resolution came from experiment. In 2007, Meyer and colleagues suspended single graphene sheets on a microfabricated scaffold in vacuum or air and examined them by transmission electron microscopy. The membranes were one atom thick yet still showed long-range crystalline order. They were not perfectly flat, however. They showed intrinsic microscopic roughening, with the surface normal varying by several degrees and out-of-plane deformations reaching about 1 nm. The authors suggested that these ripples may help explain why such crystals are stable [16]. A two-dimensional crystal in three-dimensional space can lower its energy by crumpling gently in the third dimension.

The practical lesson for later chapters is humility in both directions. Bulk products are not proofs of textbook monolayers. And a textbook monolayer is not proof that every drum labeled graphene will behave like the sheets in Manchester’s devices.

1.5 Cages and tubes: 1985 and 1991 train a generation

In 1985, Harold Kroto, James Heath, Sean O’Brien, Robert Curl and Richard Smalley reported C_{60}, buckminsterfullerene, in *Nature*: sixty carbon atoms closed into a truncated icosahedron [17]. sp^2 carbon, it turned out, did not have to be flat graphite or tetrahedral diamond. In 1991, Sumio Iijima’s *Nature* paper on helical microtubules of graphitic carbon introduced multiwall carbon nanotubes [18]. The image of a nanotube as a rolled-up graphene sheet made “graphene” a familiar concept to a generation of researchers, years before anyone held one.

Those years mattered for another reason. Characterization habits forged on fullerenes and nanotubes, such as Raman fingerprints of sp^2 carbon, high-resolution electron microscopy, and a culture of linking nanostructure to properties, moved straight into graphene laboratories. So did the commercial lesson. Carbon nanotubes went through their own cycle of excitement and slow industrialization, and their supply chains later diverged from graphene’s even as their applications overlapped (Chapter 12).

1.6 The flying frog and the Friday-night habit

Before graphene made Andre Geim famous among materials scientists, a frog made him famous to everyone else. In the late 1990s, Geim’s group at Nijmegen levitated a variety of objects, including a living frog, in a magnetic field of about 16 tesla. Water and most organic matter are weakly diamagnetic, repelled by magnetic fields, and in a strong enough field gradient that tiny repulsion can balance gravity. With Michael Berry, Geim explained why the levitation is stable despite Earnshaw’s theorem: the theorem does not apply to induced magnetism, and stable zones exist on the axis of a rotationally symmetric field [19]. The work earned Geim and Berry the 2000 Ig Nobel Prize in Physics, and Geim remains one of very few people to hold both an Ig Nobel and a Nobel Prize [2].

Geim has described his “Friday night experiments” as low-stakes, curiosity-driven projects outside a laboratory’s main work, most of which fail [2]. Graphene’s isolation is often flattened into “they used

Scotch tape." Geim's own account goes further. Tape helped. Oxidized silicon made thin flakes visible as interference colors. The decisive step was measuring the electric field effect in crude early devices, then progressing to thinner crystals and proper Hall-bar geometries [2, 3]. Popular myth stops at stationery. The paper that changed the field stops at transport measurements.

1.7 2004: rejected by Nature, published by Science

The Manchester team, with collaborators in Chernogolovka, Russia, first submitted its results to *Nature*. Geim later recalled that the manuscript was rejected twice, with one referee judging that it did not constitute a sufficient scientific advance [2]. The team took the work to *Science*. On 22 October 2004, Novoselov, Geim, Morozov, Jiang, Zhang, Dubonos, Grigorieva and Firsov published "Electric Field Effect in Atomically Thin Carbon Films" [1].

The abstract is worth reading closely. It describes monocrystalline graphitic films "a few atoms thick" that are nonetheless stable under ambient conditions, metallic, and of remarkably high quality. The films behave as a two-dimensional semimetal with a tiny overlap between valence and conduction bands. They show a strong ambipolar electric field effect, so that electrons or holes at concentrations up to 10^{13} per square centimeter, with room-temperature mobilities of about 10,000 $cm^2\ V^{-1}\ s^{-1}$, can be induced by a gate voltage [1]. Sticky tape is the folklore. Gated devices are the science.

Buyers inherit a trap from that fame. The celebrated flake on a silicon wafer is not what most industrial dispersions contain. Mobility and crystallinity benchmarks from 2004 set a quality ceiling that few-layer powders and reduced graphene oxide grades rarely claim, and often do not need, for concrete, grease or coolant duty. Confusing the Nobel flake with the drum is how hype is born (Chapter 12).

1.8 2005–2009: landmarks that still echo in sales decks

Between discovery and Stockholm, laboratories raced to measure what a clean sheet could do.

In November 2005, two papers in the same issue of *Nature*, one from Manchester and one from Philip Kim's group at Columbia, showed that graphene's charge carriers behave as massless Dirac fermions. The Manchester team reported an effective "speed of light" of about 10^6 m s^{-1}, a conductivity that never falls below a minimum value near the quantum unit even as carrier density approaches zero, and an anomalous half-integer quantum Hall effect [20]. The Columbia team independently observed the quantum Hall effect and the Berry's phase expected for Dirac carriers [21]. In 2007, the quantum Hall effect was measured in graphene at room temperature, where previously it had required liquid-helium temperatures [22]. Geim and Novoselov's review "The rise of graphene" that year set the agenda for the field [5].

In 2008, four measurements produced the numbers that still headline marketing. At the University of California, Riverside, Alexander Balandin's group suspended single-layer graphene over trenches and used the temperature-dependent Raman G peak as an optical thermometer. They extracted room-temperature thermal conductivities of about $(4.84 \pm 0.44) \times 10^3$ to $(5.30 \pm 0.48) \times 10^3$ W $m^{-1}\ K^{-1}$ [23]. At Columbia, Changgu Lee, Xiaoding Wei, Jeffrey Kysar and James Hone pressed an atomic force microscope tip into suspended monolayers and reported a Young's modulus of about 1.0 TPa and an

intrinsic strength of about 130 GPa [24]. In Manchester, Rahul Nair and colleagues showed that a suspended monolayer absorbs about $\pi\alpha \approx 2.3\%$ of white light, a value set by the fine-structure constant [25]. Bolotin and colleagues at Columbia reported electron mobilities above 200,000 $cm^2\ V^{-1}\ s^{-1}$ in suspended, current-annealed devices [26]. Chapters 4 to 8 unpack these experiments, and in particular the word “suspended” that marketing tends to drop.

Meanwhile, the manufacturing routes diverged. Hernandez and colleagues at Trinity College Dublin demonstrated liquid-phase exfoliation of graphite in solvents such as N-methyl-pyrrolidone, a route toward inks and additives [27]. Li and colleagues at the University of Texas at Austin grew centimeter-scale, predominantly single-layer films on copper foil by chemical vapor deposition, a route toward wafers and transparent electrodes [28]. Chapter 3 describes the factories those papers implied.

1.9 Stockholm, 2010, and the morning after

The Royal Swedish Academy of Sciences awarded the 2010 Nobel Prize in Physics to Andre Geim and Konstantin Novoselov “for groundbreaking experiments regarding the two-dimensional material graphene” [29]. Geim’s lecture, “Random Walk to Graphene,” and Novoselov’s, “Graphene: Materials in the Flatland,” remain the primary autobiographical accounts [2, 3]. Only six years separated the key paper from the prize, unusually fast by Nobel standards.

Funding, start-ups and national programs followed. In 2012, Novoselov and colleagues published “A roadmap for graphene” in *Nature*, matching production methods to the applications each could support [30]. Europe’s Graphene Flagship, launched in 2013, became one of the largest coordinated research efforts the continent had attempted, and its 2015 science and technology roadmap ran to more than 200 journal pages [31]. Production routes multiplied: liquid-phase and shear exfoliation, electrochemical exfoliation, oxide routes, CVD on copper, epitaxial growth on silicon carbide and, in 2020, flash Joule heating of waste carbon at Rice University [32–35]. In 2014, Coleman’s group at Trinity showed that a kitchen blender and household detergent could exfoliate graphite at meaningful rates, because the turbulent shear exceeded the critical value for exfoliation [36]. The blender is a parable: the industrial problem is delivering shear and stabilizing what is peeled, not magic. Standards bodies tried to discipline the vocabulary, with ISO/TS 80004-13 published in 2017 and revised in 2024 [6, 7].

Applications advanced unevenly. Composites, coatings, energy-storage additives, thermal management and construction materials found real niches. Graphene digital logic, the application many expected first, largely did not arrive, for reasons explained in Chapter 5. A 2018 survey of 60 producers found that much of the material sold as graphene was closer to graphite microplatelets [37]. The morning after the Nobel turned out to be a long one, and Chapter 12 tells that part of the story.

1.10 Where Charlotte enters the timeline

Manchester and Stockholm are not Charlotte, North Carolina, and this book keeps that distance deliberately. Graphene Integrations (GI) is a US graphene manufacturer in the Charlotte, NC area. It produces graphene by exfoliation and supplies it already dispersed in carriers (water, solvents, resins and oils) rather than as dry powder [38, 39]. Its sister company, Nano Technology Chemicals (NTC), is a

chemical distributor and toll blender [40]. GI's published product results appear in this book only in clearly marked "lane B" passages (Chapter 10) and in Chapter 13, with the test context the company states. The peer-reviewed history remains the spine of the book. Company material appears where a purchaser needs to know what is actually for sale.

1.11 Timeline (selected)

Table 1.1. Selected milestones in the history of graphene.

Year	Event	Reference
1859	Brodie oxidizes graphite while determining its atomic weight	[8]
1947	Wallace's band theory of graphite	[4]
1958	Hummers and Offeman publish the permanganate route to graphitic oxide	[9]
1962	Boehm and colleagues report very thin carbon foils from reduced graphite oxide	[11]
1968	Mermin's theorem on crystalline order in two dimensions	[15]
1985	C_{60} buckminsterfullerene	[17]
1986	Boehm, Setton and Stumpp propose the name "graphene"	[12]
1991	Iijima's multiwall carbon nanotubes	[18]
1994	IUPAC recommendations adopt "graphene"	[13]
1997	Berry and Geim explain diamagnetic levitation (the "flying frog")	[19]
2004	Electric field effect in atomically thin carbon films	[1]
2005	Massless Dirac fermions and the half-integer quantum Hall effect	[20, 21]
2007	Suspended sheets show ripples; room-temperature quantum Hall effect	[16, 22]
2008	Landmark thermal, mechanical, optical and mobility measurements; liquid-phase exfoliation	[23–27]
2009	Large-area CVD graphene on copper	[28]
2010	Nobel Prize in Physics to Geim and Novoselov	[29]
2014	Shear exfoliation scales to hundreds of liters	[32]
2017	ISO/TS 80004-13 vocabulary (revised 2024)	[6, 7]
2018	Survey of 60 producers questions market classifications	[37]
2020	Flash graphene from waste carbon	[34]

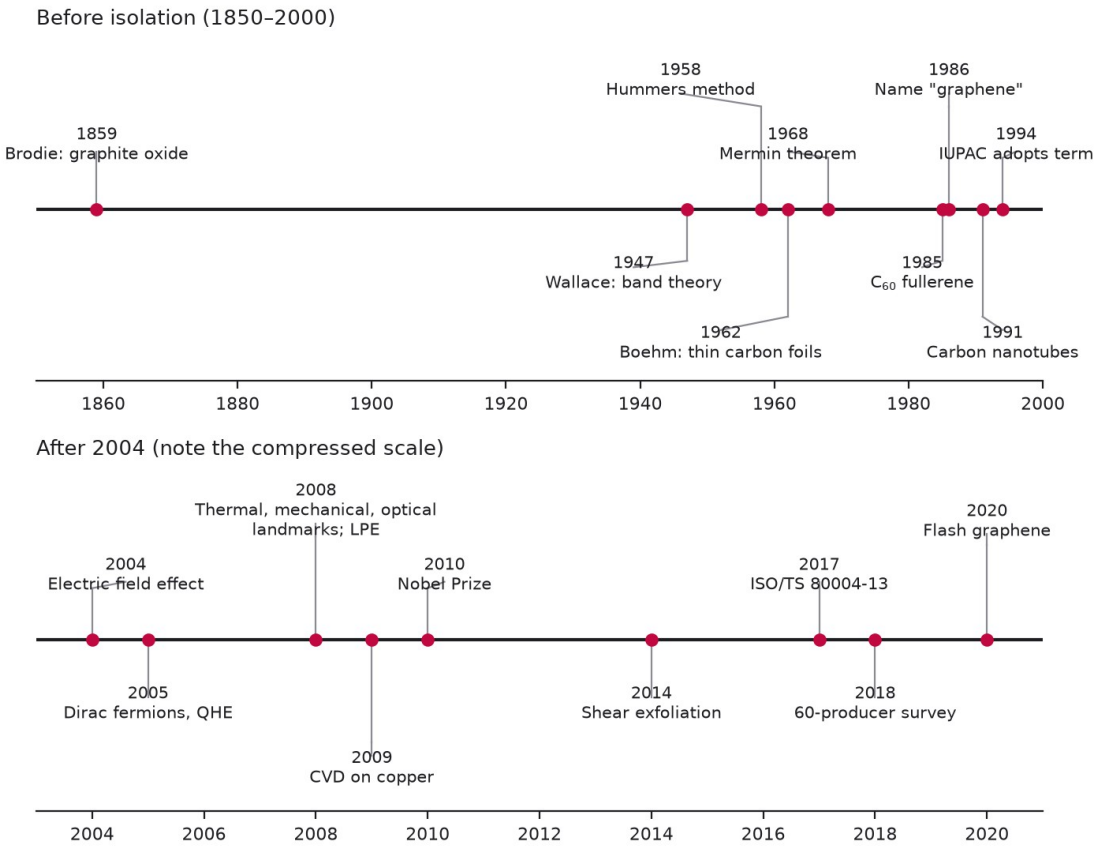

Figure 1.1. Selected milestones on a time axis, from Brodie's graphite oxide (1859) to flash graphene (2020). The crowding of events after 2004 shows how quickly a measured material drew the field.

History leaves a practical question on the table. When a label says graphene, which chapter of this story is inside the drum: Wallace's lattice, Boehm's chemistry, Manchester's monolayer, a sheared few-layer flake, flash carbon, or something looser? Chapter 2 picks up that question with definitions, layer counts, and the ISO language that keeps purchases honest. Graphene Integrations' introductory pages offer a non-technical companion: What is graphene? and How we make graphene.

Thanks for reading Chapter 1

The full book continues with what graphene is, how it is made, its thermal, electrical, mechanical, barrier and optical properties, dispersions, applications by industry, safety and standards, and the market.

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