# Opportunities in Carbon-Based Inks, Pastes, and Coatings for Electronics Applications: 2010

## Chapter One

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**About the Report:**



For decades, carbon inks, pastes and coatings have generated substantial revenues in the electronics industry from applications as diverse as membrane switch electrodes to EMI/RFI shielding. In recent years, however, this rather traditional part of the electronic materials market has seen new business opportunities emerge as carbon nanotubes have entered the market. In the not-too-distant future, graphene formulations also have the opportunity to revolutionize the market.

Some of the first high-volume applications of carbon nanotubes and graphene will be to boost the performance of conventional products for equally mature applications. But carbon nanotubes and graphene also enable some completely new applications--such as nanotube-based transparent conductors for the display industry and nanotube-enhanced supercapacitors for the coming "smart" electricity grid.

This report contains NanoMarkets' in-depth analysis and forecasts for carbon inks, pastes, and coatings for electronics applications. While the replacement of silicon with carbon nanotubes and graphene lies far in the future, the use of these materials in conductive coatings and as an enhancement for currently-used carbon materials is very much a near-term opportunity. This report is essential reading for marketing executives and business development managers in the coatings, function inks and nanomaterials businesses, as well as those planning the future of electronic devices.

# Table of Contents



## Executive Summary



## Chapter One: Introduction



## Chapter Two: Carbon Inks, Pastes, and Coatings-Products and Materials

## Chapter Three: Markets for Carbon Inks, Pastes, and Coatings





## Chapter Four: Eight-Year Forecasts of Carbon Inks, Pastes and Coatings for Electronics

## List of Exhibits

# Chapter One: Introduction

## 1.1 Background to this Report



Carbon materials have been an important part of electronics throughout the industry's history. But far from being a stagnant class of materials, new developments in carbon materials are poised to dramatically improve the performance in the applications that use them as well as enable completely new applications. Eventually, these new classes of materials may even revolutionize the electronics industry as we know it.

Conventional carbon inks, pastes, and coatings make up a critical—if sometimes overlooked—class of materials in the electronics industry, providing solutions that are modestly conductive as well as cheap, easy to apply, and inert. Carbon is thus an important entry in the portfolio of materials used for conductive coatings, especially when extremely low resistivity is not required. While these conventional materials and applications are certainly not the most exciting in the electronics industry, they have been a consistent source of revenues. But now new breakthrough materials—carbon nanotubes and graphene—are breathing new life into the carbon materials market and making carbon indeed "sexy." Nanocarbon materials are already enabling new applications that take advantage of conductivity much higher than that of any metal. Down the road—though too far away to be the main focus of this report—are even more possibilities that could provide carbon the status that silicon currently holds in the electronics industry.

### 1.1.1 Conventional Carbon Materials

Conventional carbon inks, pastes and coatings are big business. Such thick-film carbon coatings are used in numerous applications including capacitors, membrane switches, keypads, printed circuit boards, EL lighting, and batteries. In addition to these, some newer and rapidly growing applications are providing growth markets for these conventional carbon inks, pastes, and coatings. These include: photovoltaics; energy storage, which is becoming more and more important as the smart grid is developed; and EMI/RFI shielding and anti-static coatings as electronics and components become ever more sensitive to interference and electrostatic discharge (ESD). In photovoltaics, conventional carbon is largely used in CdTe PV as carbon paste for the back contacts, but even so, the rapid growth of CdTe PV has made this a growth market for carbon. Conventional carbon is also a contender as a catalyst in dye-sensitized cell (DSC) PV, to replace costly platinum.

Also approaching a stage of rapid growth is the supercapacitor market, in which carbon provides a high-surface area material for the storage of large amounts of electrical charge.

Demand for these supercapacitors will increase to accommodate decentralized electricity storage as electricity generation becomes more distributed—through the growth of photovoltaics and other alternative generation technologies at smaller than utility-scale—and as the smart grid is deployed. To some extent, these phenomena will also boost demand for rechargeable batteries, many of which also use carbon inks and coatings.



And as low-cost, flexible electronics begins to emerge for applications such as RFID, the need for thin-film and printed batteries—often using carbon—will increase as well. Carbon is a mainstay of the primary battery industry and, although zinc-carbon batteries are generally mediocre in performance in old-style applications such as flashlights, they are certainly adequate—and low in cost—for some printed battery applications. Carbon is also used as an electrode for some of the lithium-based batteries, which can also be made by thin-film techniques. Also significant is the need for low-cost antennas for RFID, and carbon has been demonstrated for some types of these antennas.

### 1.1.2 Carbon Gets Interesting: Mixtures, Composites, and New Materials

Besides being an important conductor when used by itself or as the major component of a composite paste, carbon can also be especially useful in combinations with other materials. This includes mixtures (e.g., carbon-silver pastes) as well as combinations of different discrete pastes (e.g., carbon paste applied on top of silver paste). Carbon need not be the major component of the inks, pastes, and coatings it is used in; for instance, mixtures of carbon and silver or carbon and copper can be formulated to target a wide range of electrical, thermal, and chemical properties. Here lie applications such as resistive heaters for automobiles, or resistors in general. And the conductivity of a mixture of carbon and a metal such as silver behaves in a non-linear fashion. Adding carbon in small to moderate quantities to silver has only a small effect on the conductivity; thus silver—or another metal—can be mixed with carbon to reduce costs, without sacrificing much in performance.

Carbon's inertness also makes it highly desirable as a thin coating over another, more conductive material. And it is not just chemical inertness that matters here; electromigration and the formation of dendrites are physical changes in metallic layers that are extremely problematic for the devices in which the conductors are used. One important function of carbon is to provide a stable outermost coating for metals such as silver that are susceptible to electromigration; the printed carbon forms an inert, conductive encapsulant against dendrite formation on silver inks and other metals. Carbon is used in this way in switches and other devices that primarily use other conductive materials like silver. The thin layer of carbon produces only a small increase in series resistance.

While there are many applications for conventional carbon materials, and many of them are quite lucrative, these conventional materials are obviously not all that carbon is about. Newer carbon materials have been discovered and developed in recent years, materials that promise to enhance the properties of carbon, in some cases far beyond those of any material known before. Outside of the research labs, these new carbon materials have also drawn the interest of investors and capitalists who see their potential in the commercial electronics world.



These new materials are the nanoscale phases of carbon—carbon nanotubes, fullerenes, and graphene sheets—and their electrical and physical properties are truly impressive. Carbon nanotubes, depending on the nanotube structure, can either have extremely high electrical conductivity, higher than that of any metal, or be semiconducting. Carbon nanotubes also posses extremely high thermal conductivity—also much higher than that of any of the metals—and are the strongest known materials in tension. Graphene, depending on the dimensions of the sheet, can also have high thermal conductivity and either high electrical conductivity or semiconductivity. Fullerenes—the so-called “buckyballs” or hollow carbon spheres—are good electron acceptors and have been used in OPV cells.

These carbon nanomaterials—when added to or used in place of conventional carbon materials—can lend their enhanced properties to the applications that use them. In this way, thick-film carbon materials can gain new life as high-end conductive inks and pastes while still remaining low in cost. But they also open the door to completely new applications. For instance, the high conductivity of certain carbon nanotubes has hinted at their ability to form wires more conductive than copper or silver, and their tiny size makes possible the formation of films that are uniformly conductive on the macro scale and even on the micron scale, yet thin enough to be highly transparent.

### 1.1.3 Carbon Nanotubes Come Into their Own

This high electrical conductivity in a diffuse film is in fact the property behind some of the most lucrative new applications for carbon nanotube inks: highly conductive films, including transparent ones. But carbon nanotubes are not all the same; only some are conductive while others are semiconductive. In fact, one of the key areas of research—and limits on their commercial usefulness—is focused on how to produce only a single type of nanotube or separate the conductive ones from the semiconductive ones. Mixtures containing both types of carbon nanotubes are still quite conductive and suitable for the new classes of applications, but there is a lot of room for improvement—and additional, more demanding applications—as the technological hurdles are overcome.

Beyond the electrical conductivity of carbon nanotubes, their thermal conductivity is drawing interest for applications such as heat spreaders and heat sinks, while the mechanical properties suggest uses in mechanically operating computer memories and other nanometer scale switching applications. Further out are applications that make use of the semiconductivity of certain nanotubes, such as single-nanotube transistors and other electronic devices. Significantly, these single-nanotube applications were widely believed to be on the verge of commercialization as recently as five years ago but have since taken a back seat to the conductive applications in terms of progress toward wide commercialization.

#### 1.1.4 Graphene: Finding Its Way

Even newer on the scene is graphene, the single-atom-thick graphite monolayer that can also be either very conductive or semiconductive depending on sheet structure and dimensions. While continuous sheets of graphene are frequently envisioned as making up the surface of semiconductor chips in the future—as the successor to silicon—even producing a single large sheet of graphene still maxes out our current technological abilities. In fact, for all of its potential, graphene is still widely made by the very low-tech method of peeling layers off of bulk graphite!

While many graphene researchers are quite exuberant about the commercial prospects for graphene, a cautious view suggests that—as was the case for carbon nanotubes—the most dramatic, truly novel applications are still several years away. Graphene is thus likely to be a material mainly for niche applications for many years. But those niches are already beginning to emerge and products such as graphene inks are already nearing commercialization.

### 1.2 Objectives and Scope of this Report

The primary objective of this report is to analyze the markets for carbon inks, pastes, and coatings and to translate these analyses into a thorough examination of the opportunities for these materials—both the conventional ones and the ones made with carbon nanotubes or graphene—and for the firms that produce them. This analysis includes both technical and business issues, such as identifying what these carbon materials have to offer and what increasing volumes will do for production costs. And for the newer nanocarbon materials, which are still only partially understood, there are still many opportunities for true “breakthroughs,” the likelihood of which must be taken into account.

A separate but related goal of this report is to provide detailed forecasts of the markets for carbon inks, pastes, and coatings both in volume terms and in monetary terms, from the view of the different material types and their various applications. Such an analysis is difficult in the current environment, with uncertainty in virtually every relevant aspect of the economy. Loss of demand due to the recession has led to overcapacity and even oversupply in several segments of the electronics industry, while the combination of reduced demand and economic uncertainty has caused commodity prices to behave in unusual ways. Energy prices are still down significantly in this economy, making the future levels of demand for "green" applications—some of which are important markets for carbon inks, pastes, and coatings—uncertain. And since carbon is often a substitute for costly commodities such as silver, volatile commodity prices can affect the relative penetration of carbon vs. these other materials.

It is now widely believed that the worldwide economy is in the beginnings of a recovery. But the nature of a recovery following such a deep recession is highly uncertain and it is far from certain that the economy will grow at anything like a normal pace from here on out. The current combination of economic factors and uncertainties as to what the future holds makes it difficult to reliably quantify the markets for the materials covered in this report, but that is what we have done.

This report is international in scope. The forecasts herein are worldwide forecasts and we have not been geographically selective in the firms that we have covered in this report or interviewed in order to collect information.

### 1.3 Methodology of this Report

To thoroughly assess the markets for carbon inks, pastes, and coatings, we have taken a two-pronged analysis. We have analyzed the materials themselves—how do they compare to other materials, can they be cost effective, will volumes be sufficient—as well as the applications and markets—why are new materials required and what will they bring to the applications in terms of performance and cost. These analyses are necessarily different for the existing materials and applications than for those just emerging or still yet to emerge. The "supply side" of our analysis focuses largely on the activities of carbon materials firms in producing and developing the materials—both the carbon itself and the inks, pastes, and coatings formulated with it—while the "demand side" focuses on the applications and the market needs for the materials.

In the course of our analysis, we assess the existing carbon materials, the materials with which they compete, and the key factors influencing the use of one type of material over another in the various applications. We also assess the anticipated growth of the applications in which the carbon materials can be used and the key features of carbon—especially the nanocarbon materials—that may influence the penetration of these materials into each market.

The information for this work is derived from a variety of sources, but principally comes from primary sources, including NanoMarkets' ongoing interview program of technologists, business development managers, and academics involved with emerging electronics of all kinds, including thin-film and printable electronics. We also drew on an extensive search of the technical literature, relevant company Web sites, trade journals, government resources, and various collateral items from trade shows and conferences. By nature of the similar application areas, some of the data for this report has also been used in other NanoMarkets' reports including, "*Silver Inks and Pastes: 2009 to 2016*" and "*Conductive Coatings Markets, 2009 and Beyond*," but this report is largely a new endeavor. In the cases where information has been used in an earlier report, it has been reinvestigated, reanalyzed, and reconsidered in light of current developments, and updated accordingly.

The forecasting approach taken in this report is explained in more detail in Chapter Four, but the basic approach taken here is to look at the underlying needs and markets, as well as the technologies and types of products available or under development, to assess suitability and likely volume over the next eight years. The stated plans of the key firms are of course of special interest, although NanoMarkets critically considers these claims in light of all available data.

### 1.4 Plan of this Report

In Chapter Two, we consider the primary carbon products and materials—carbon itself in conventional and nano form as well as the inks, pastes, and coatings that incorporate it—from technical, technological, and volume perspectives. In Chapter Three, we discuss the markets for the materials, including traditional applications (i.e., thick-film applications) and the newer applications that are enabled by carbon nanotubes and graphene. Chapter Four contains our eight-year forecasts of the markets for carbon inks, pastes, and coatings by application and by material type.

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