Vor-ink™ - Graphene-based inks and Coatings for Printed Electronics and Coated Conductives

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Director, Development

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Graphene

Sheets of carbon – a single-atom thick
Exceptional strength, stability
Unique electrical, thermal properties
Subject of the 2010 Nobel Prize in physics

“Graphene is a rapidly rising star on the horizon of materials”

“Upon bending and stretching, the sheets retain their useful properties.”
M. Jacoby, C&E News, 2009

“Graphene continues to amaze — Is there anything graphene can’t do?”
Hamish Johnston, Physics World 2008

Vorbeck Vor-x™ and Vor-ink™ for printed electronics
World’s first commercial graphene-based products
Vorbeck Materials Corp.

Corporate Headquarters – Jessup, MD
Vorbeck Princeton Research Center – Princeton, NJ
Founded in 2006

Vorbeck Inks and Coatings
Electrical, thermal, and optical properties applied in consumer goods and packaging, sensors & medical diagnostics, and aerospace coatings

Vorbeck Performance Materials
Multifunctional and high-strength composites with applications in automotive, military, wind-power markets

Vorbeck Energy
Energy storage materials with exceptionally high performance for use in electric vehicle, military, and portable electronics markets
Conductive ink and coating formulations

World’s first mass-market graphene-based commercial products

Enabling printed electronics applications in consumer goods, medical, industrial, and aerospace applications

Vorbeck is the only company with EPA approvals for the commercial manufacture and sale of graphene-based products
Vor-x™ Graphene

Base technology licensed from Princeton University

High fraction (80%) single sheet

Lateral dimensions 0.1 – 50 microns

Less than 1nm thick

Functionalized surface
Vor-x™ - Wrinkled morphology


Vor-x™ - Functionalized Graphene Sheets

Exfoliation of graphite produces Functionalized Graphene Sheets (FGS)

Epoxy, carboxyl and hydroxyl function groups provide reaction points for additional chemical modifications – tailor-made products

Wrinkled morphology of FGS prevents restacking of sheets, or rolling up into carbon nanotubes (CNTs).
Vor-x™: Properties

Graphite Oxide

Graphene

Transmission Electron Microscopy (TEM)

Scanning Electron Microscopy (SEM)

0.2 g

0.2 g
Printed electronics

A paradigm shift in electronics
From traditional subtractive etching processes
to low-cost roll-to-roll additive printing processes
Enormous market opportunity ($46 Billion by 2016)

Change in the cost structure
Processing costs decrease dramatically
Material costs increase
(silver inks instead of etched copper or aluminum)
Silver inks and carbon inks each >$1 billion markets by 2015

Ink processibility is key
Low processing temperatures critical for inexpensive substrates
Runnability and stability crucial for high-resolution flexo/gravure printing
Flexibility and robustness of material are key properties
Conventional conductive inks/coatings

<table>
<thead>
<tr>
<th>Method</th>
<th>Advantages</th>
<th>Disadvantages</th>
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<tbody>
<tr>
<td>Etched circuits</td>
<td>Precision, reliability, performance, lifetime</td>
<td>Expensive, multi-step, subtractive, generates chemical waste</td>
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<tr>
<td>Silver inks</td>
<td>Conductivity, oxidative stability</td>
<td>Expensive, high-temperature cure, needs sintering for maximum conductivity</td>
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<tr>
<td>Copper inks</td>
<td>Conductivity, less expensive than Ag</td>
<td>Oxidizes/loses conductivity, heavy, high-temperature cure, needs sintering for maximum conductivity</td>
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<tr>
<td>Other metal inks</td>
<td>Less expensive than Ag or Cu</td>
<td>Oxidizes/loses conductivity, not as conductive as Ag or Cu</td>
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<tr>
<td>Conductive polymers (PANI, PEDOT:PSS)</td>
<td>Low-cost, transparency, light weight, flexible</td>
<td>Low conductivity, difficult to formulate due to low solubility</td>
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<tr>
<td>Carbon inks</td>
<td>Low-cost, light-weight</td>
<td>Lower conductivity, conductivity stability, poor flexibility</td>
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<tr>
<td>Carbon nanotubes</td>
<td>As conductive as metal-oxides (eg. ITO), transparency</td>
<td>Difficult to process, poor dispersion stability, batch-to-batch variability</td>
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Graphene-based inks overcome the price vs. performance challenges of existing technologies
Conductive inks and coatings for Printed Electronics

Vor-ink advantages:

Price – much less expensive than competing silver (5x cost savings)

Performance – 10-100x better than other carbons, excellent flexibility, does not corrode.

Processing – low-temperature curing, no change in manufacturing, standard commercial printing presses, compatible with a wide variety of substrates

Exceptional conductivity and flexibility enable myriad applications for printed electronics and coated conductives
Coating Methods
- Slot-die
- Rod coating
- Blade coating
- Roll coating

Printing Methods
- Screen printing – Flat bed and rotary
- Gravure/flexo printing
- Inkjet (in development)

Vor-ink™ F-series and S-series inks can be tailored to a wide variety of coating and printing methods
Vor-ink™: High-speed flexo

High-print speeds (over 200 fpm)
Vor-ink™: SEM
Film quality and adhesion

SEM images of Vor-ink films
Cohesive films over a wide range of thicknesses, even down to 1 micron
**Vor-ink™: Performance**

### Conductivity

<table>
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<th>Normalized Conductivity</th>
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<tr>
<td></td>
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<tr>
<td>Carbon ink</td>
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<tr>
<td>Vor-ink S-series ink</td>
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</tbody>
</table>

### Crease resistance

![Graph showing crease resistance comparison between Vor-ink S-series ink and Commercial Carbon Ink.](image)

- **Percent Retention of Conductivity**
- **Number of Creases**
- **Vor-ink S-series ink**
- **Commercial Carbon Ink**

(*Measured after application of a 0.5 lb weight to a 180° crease for 1 min*)

### Adhesion

- **No transfer** (5B Cross-cut Adhesion Test – ASTM D3359-08B)
- **<1% change in resistance** (Sutherland Rub – 200 strokes with 4 lb. weight)

### Flex Resistance

- **<5% increase in resistivity**, after 100 180° bends over a 3 mm mandrel
Vor-ink™ applications
consumer goods & smart packaging

Vor-ink - enabling item-level printed electronics for consumer goods

Conductors, electrodes, and antennas to enhance consumer goods and packaging

Tagging and sensing

Authentication and anti-counterfeit

Sinter-free processing

Printing directly onto paper, label stock, and polymer films using standard printing and coating lines

Can be printed in same line with graphic inks

“Peel-and-stick electronics”
Vor-ink™ applications
Coatings

Aerospace coatings
Building material coatings
Large area antennas, detectors, and displays
Smart flooring
Light-weight, low-cost, thin, conformal, corrosion-resistant and flexible
Vor-ink™ applications
Printed electronics

Flexible displays
Switches and keypads
Heaters
Smart cards
Direct replacement for existing inks with material and processing cost advantages
Excellent flexibility
Vor-ink™:
Application case study
Cost of retail theft

Retail theft is a $115+ billion problem

Theft totals ~ 2% of retail revenues in an industry where profit margins are 4 – 6%

Some unexpected items present the largest theft risk/cost
Solutions are needed at the item level and must be affordable
Problematic existing solutions

Current solutions include locked display cabinets, external cases, or bulky alarms

Problems for Brand Owners, Retailers, and Consumers
Cost-effective security solution

MWV Natralock® with Siren Technology®, enabled by Vor-ink™

Vor-ink™ printed circuits in item-level anti-theft protection for consumer-goods
Coatings Product Possibilities

-Wide-area printing and coating on various substrates (PET, wovens, non-wovens) enable smart electronic on large-surfaces such as flooring, seating, etc.

-Example: The thermal conductivity of Vor-ink™ provides very uniform temperature distribution for heated seating

-Example: The electrical properties of Vor-ink™ enables its use for smart flooring with sensing capabilities

-Example: The flexibility combined with conductivity of Vor-ink™ enables its use for coatings with grounding, charge dissipation or shielding properties
Vor-ink™: Roll-to-roll printing
Vor-x™ in polymeric systems
- barrier properties

Relative Permeation

normalized against neat system

0.0 0.2 0.4 0.6 0.8 1.0 1.2

1.00 0.95 1.00 1.00 0.77 0.76 0.24

PDMS (1.5 wt%) Vector™ SIS (2.25 wt%) natural rubber (5 wt%)

permeability tests conducted with neat polymer system, clay (organo-montmorillonite), and Vor-x™

Opportunities in extruded polymer coatings
Vor-x™ in polymeric systems
- Tensile strength and conductivity

**Matrix**
Natural Rubber
PMMA
Natural Rubber
Natural Rubber

**Loading**
4% Vor-x
4% SWNT$^1$
40% CB
20% CB$^2$

**Conductivity (S/m)**
0.3
0.01
0.01 - 1
10$^{-9}$

1: Du et al. J. Poly Sci. Part B, 41, 3333
Vorbeck: graphene by the ton

Strong Intellectual Property
50+ patents & applications in area

Multi ton-scale plant
Running since 2007
Capacity to meet needs
EPA approvals
New plant under design in Pocomoke City, MD

Vor-ink
Ready-to-print formulations commercially available
World’s first graphene-based product

Vor-charge
High-performance battery electrode materials

Vor-x Composites, Sensors & Optics
Plastic and elastomer composites with development partners
Sensors and materials with controlled optical properties
Vorbeck Materials Corp.  
Products to Market

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