NanoIntegris

The world's leading supplier of electronically pure

Metallic and Semiconducting Single-Walled Carbon Nanotubes

and Graphene

Up to

99%

Purity

Products

Single-Walled Carbon Nanotubes (SWNTs)

IsoNanotubes-S™
Semiconducting SWNTs

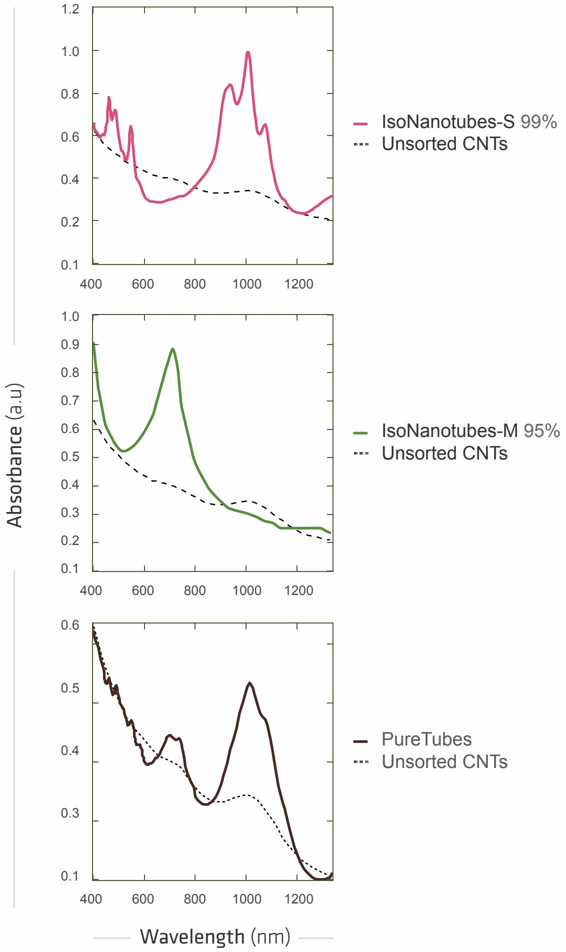
Diameter Range: 1.2 nm-1.7 nm
Length Range: 300 nm to 4 microns
Metal Catlyst Impurity: <1%
Amorphous Carbon Impurity: 1-5%
Semiconducting SWNT Enrichment: 90%, 95%, 98%, or 99%
Form: Solution or surfactant eliminated powder
Solution Color: Pink

IsoNanotubes-M™
Metallic SWNTs

Diameter Range: 1.2 nm-1.7 nm
Length Range: 300 nm to 4 microns
Metal Catlyst Impurity: <1%
Amorphous Carbon Impurity: 1-5%
Metallic SWNT Enrichment: 70%, 95%, 98% or 99%
Form: Solution or surfactant eliminated powder
Solution Color: Green

PureTubes™
Ultra Pure unsorted SWNTs

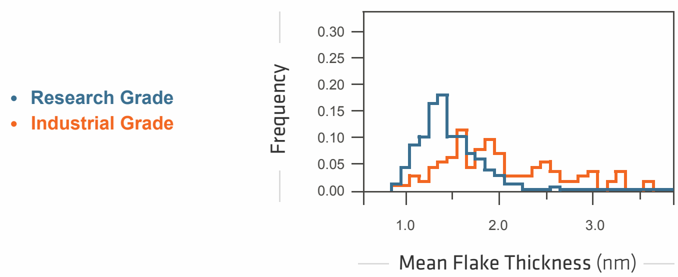
Diameter Range: 1.2 nm-1.7 nm
Length Range: 300 nm to 4 microns
Metal Catlyst Impurity: <1%
Amorphous Carbon Impurity: 1-5%
Form: Solution or surfactant eliminated powder
Solution Color: Gray



Graphene Nanomaterials

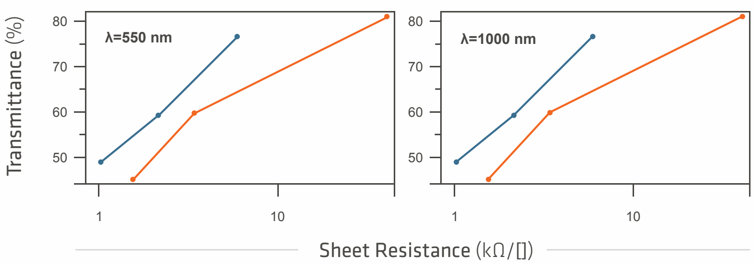
PureSheets™ - Research Grade
Graphene Nanoplatelets

Median Thickness: 1.4 nm
Concentration: 2 mg/mL
Form: Aqueous Solution
Solution Color: Gray



PureSheets™ - Industrial Grade
Graphene Nanoplatelets

Median Thickness: 1.7 nm
Concentration: 0.4 mg/mL
Form: Aqueous Solution
Solution Color: Gray



Technology

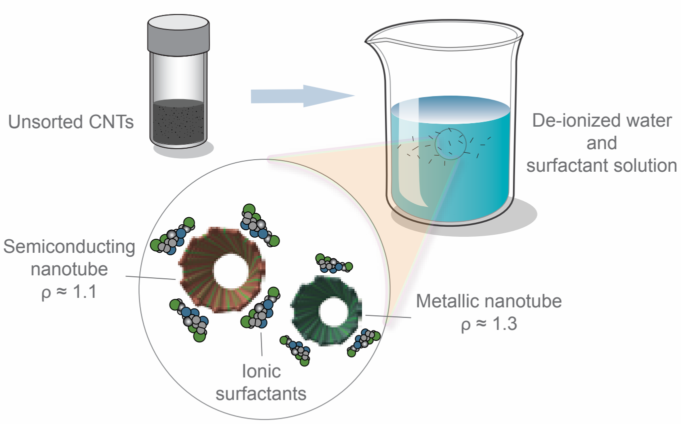
How Density Gradient Ultracentrifugation Works

Overview: NanoIntegris was founded to commercialize a technology for separating carbon nanotubes, graphene, and other nanomaterials by their optical and electronic properties. This technology, developed by the Hersam Research Group at Northwestern University, employs a technique known as density gradient ultracentrifugation **(DGU)**.

The Process

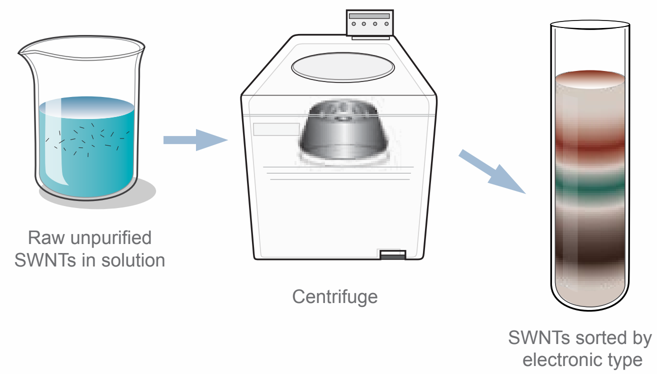
Disperse
Step 1

CNTs are dispersed in aqueous solution using a combination of surfactants. Different surfactants bind selectively to CNTs of different species, thereby augmenting the effective density difference between them.



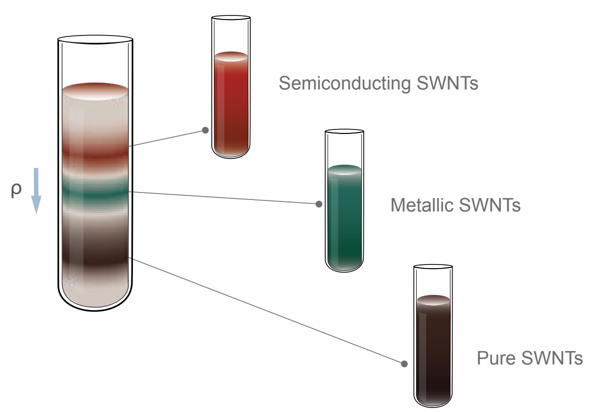
Seperate
Step 2

The CNT solution is inserted into a density gradient, and the mixture is centrifuged under a very high relative centrifugal field. During centrifugation, the surfactant-encapsulated CNTs migrate to their isopycnic (same density) point in thedensity gradient, resulting in spatial CNT separation.



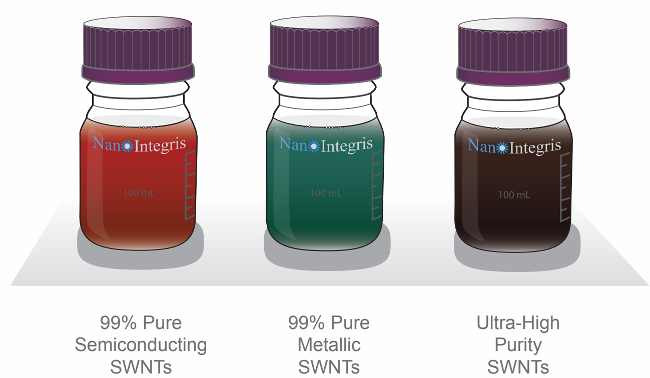
Fractionate
Step 3

The separated CNTs are isolated using established fractionation techniques.



Package
Step 4

If desired, the surfactants are removed from the separated nanotubes. The separated SWNTs are then characterized and packaged appropriately for sale.



Technology

Technology Advantages

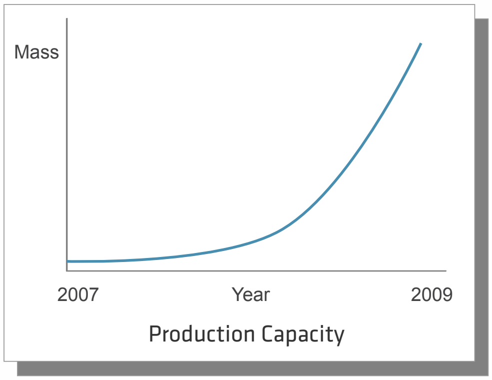
Overview: Over the last decade, several technologies have been explored to develop high purity, uniform CNTs. NanoIntegris' DGU technology offers several technical and economic advantages over alternative technologies.

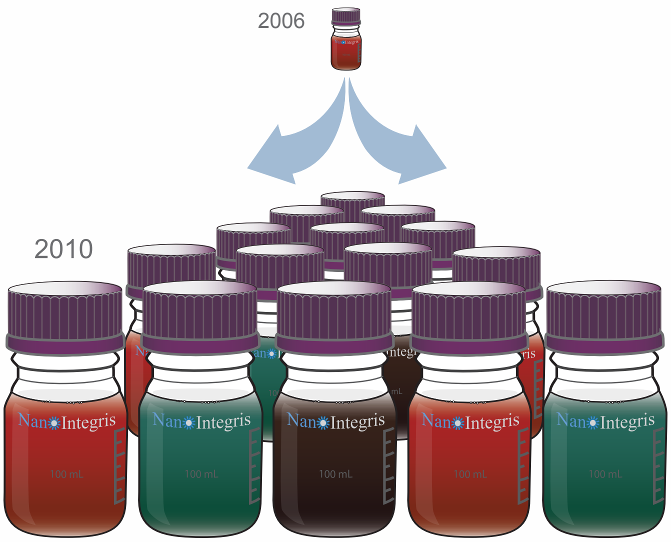
Sorting Technologies

	Density Gradient Ultracentrifugation	Electrophoresis	Chemical Selection	Electrical Breakdown	Chromatography	Selective Growth
99% Purity	✓				✓	
Versatile	✓	✓				
Scalable	✓	✓	✓	✓		✓
No Chemical Modification	✓	✓			✓	✓

Scale

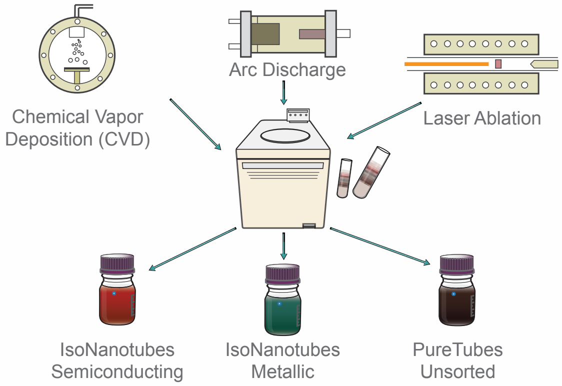
NanoIntegris has achieved over a 10,000x increase in production capacity since 2007. We are working to further increase our output and reduce our costs to serve the needs of our customers and collaborators.





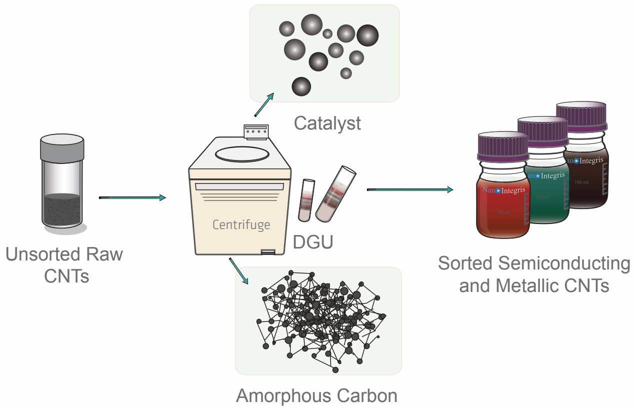
Versatility

NanoIntegris' separation technology is compatible with all established CNT synthesis methods (e.g., CVD, arc discharge, and laser ablation). It is also compatible with tubes of a broad range of diameters and lengths.



Purity

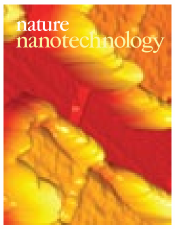
An additional benefit of NanoIntegris' separation technology is that it efficiently removes the metal catalyst and amorphous carbon impurities which occur naturally in as-grown CNTs.



Publications

Highlight DGU Advantages

The following publications highlight the advantages of DGU over competing separation technologies and demonstrate the exemplary performance of DGU-sorted nanotubes in several key applications.

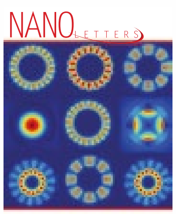


Sorting Carbon Nanotubes by Electronic Structure using Density Differentiation

Application: CNT Sorting Technologies

Citation: Arnold, M., et. al., *Nature Nanotechnology* (2006), 1, 60-65.

Summary: This foundational paper established density gradient ultracentrifugation as the technical and commercial solution to the **"carbon nanotube polydispersity"** problem. **It is the most cited paper in the history of Nature Nanotechnology**.

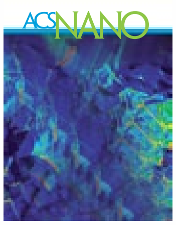


Wafer-Scale Fabrication of Separated Carbon Nanotube Thin-Film Transistors for Display Applications

Application: OLED

Citation: Wang, C., et. al., *Nano Letters* (2009), 9, 12, 4285-4291.

Summary: This paper demonstrates a functioning OLED display device based on a wafer-scale assembly of carbon nanotube thin-film transistors. Using IsoNanotubes-S 95%, the University of California produced transistors with high yield (>98%), small sheet resistance (~25 kΩ/sq), high current density (~10 μA/μm), and superior mobility (~52 cm2 V-1 s-1). Moreover, on/off ratios of >10^4 were achieved in devices with channel length L > 20 μm. To the best of our knowledge, these are the **best concurrent CNT transistor numbers reported in the literature to date.**

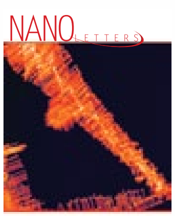


Thin Film Nanotube Transistors based on Self-Assembled, Aligned Semiconducting Carbon Nanotube Arrays

Application: Transistors

Citation: Engel, M., et al., *ACS Nano* (2008), 2, 2445-2452.

Summary: The IBM T.J. Watson Research Center with Northwestern University fabricated thin-film transistors (TFTs) from DGU produced semiconducting CNTs. To confirm the semiconducting purity of the CNTs, the team synthesized 83 single nanotube transistors from the same DGU produced source material. **82 of the 83 transistors were found to contain a semiconducting nanotube**, empirically confirming the material's calculated level (99%) of semiconducting enrichment.

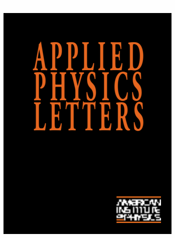


Colored Semitransparent Conductive Coatings Consisting of Monodiserse Metallic Single-Walled Carbon Nanotubes

Application: Transparent Conductive Films

Citation: Green, A., et al., *Nano Letters* (2008) 8, 1417-1422.

Summary: This paper discusses the performance of DGU-produced metallic nanotubes in transparent conductive films. In comparison to unsorted-CNT films, metallic films were found to be up to **5.6x more conductive in the visible spectrum**, and **10x more conductive in the near infrared (NIR)** at similar transparencies.



80 GHz Field-Effect Transistors produced using High Purity Semiconducting Single-Walled Carbon Nanotubes

Application: High Frequency Electronic Devices

Citation: Nougaret, L., et al., *Applied Physics Letters* (2009) 94, 243505.

Summary: In this study, solutions of 99% pure semiconducting nanotubes were used to fabricate SWNT field-effect transistors (FETs) with extrinsic and intrinsic current gain cutoff frequencies of ~15 and ~80 GHz, respectively. Importantly, this study also demonstrates that precise nanotube alignment is not required to achieve excellent performance in high-frequency devices.

Progress Towards Monodisperse Single-Walled Carbon Nanotubes

Application: CNT Sorting Technologies

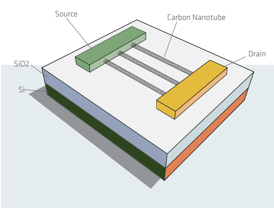
Citation: Hersam, *Nature Nanotechnology* (2008) 3, 387-394.

Summary: This paper discusses the advantages of DGU over other nanotube sorting strategies, such as dielectrophoresis, selective chemistry, controlled electrical breakdown, and chromatography. In brief, the principle advantages of DGU are its:

- ✔ Demonstrated scalability
- ✔ Compatibility with a wide range of starting materials
- ✔ Use of reversible functionalization chemistry
- ✔ Iterative repeatability

Applications

NanoIntegris materials enable a broad range of electronics, energy, and biomedical technologies. The following is a summary of several research successes by a handful of our customers and collaborators.

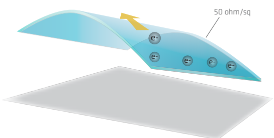


Transistors

IBM and the University of Southern California have used our IsoNanotubes-S to create TFTs with the best concurrent on/off ratios and on-drive currents reported in the literature to date.

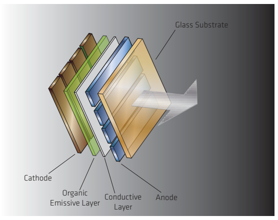
(Engel, M., et al., *ACS Nano* (2008), 2, 2445-2452.)

Semiconducting carbon nanotubes may replace or complement traditional semiconductors in both high-performance and low-cost TFT devices. Today, TFTs are most commonly used in the backplanes of LCD and OLED displays. As the flexible electronics industry matures, TFTs will likely be incorporated into a much wider range of commercial electronics.



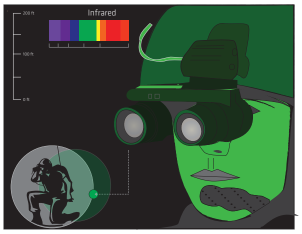
Transparent Conductive Films

CNTs have long been touted as an ideal replacement for ITO in transparent conductors. Researchers at Northwestern University (among others) have achieved near-ITO levels of performance with sorted, metallic CNTs in transparent films. (Green, A., et al., *Nano Letters* (2008) 8, 1417-1422.) Our IsoNanotubes-M are perfectly suited for this application, owing to their solution processability, flexibility, resiliency, and very high intrinsic conductivity.



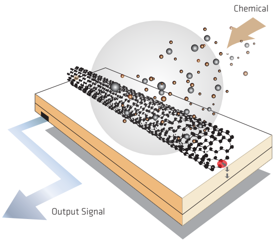
OLEDs

OLEDs have received considerable attention recently due to their limited power consumption and excellent contrast ratios. (Wang, C., et. al., *Nano Letters* (2009), 9, 12, 4285-4291.) Our IsoNanotubes-S were recently used by researchers at the University of Southern California to create OLED devices using a CNT-TFT switching mechanism.



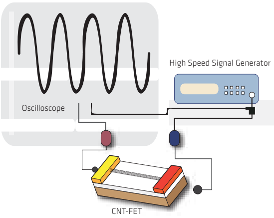
Infrared Devices

Large-diameter semiconducting SWNTs are good absorbers and emitters of light in the infrared. Moreover, high-purity SWNT thin films have been demonstrated to be photoconductive and photoluminescent under NIR illumination. IR sensors/emitters are useful for a number of military and civilian applications.



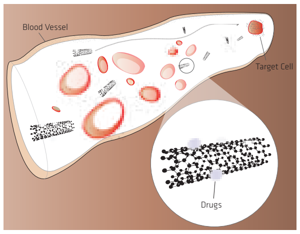
Chemical Sensors

Chemical sensors are used for many purposes, such as environmental hazard screening, explosives detection, product characterization, and medical testing. The electronic properties of SWNTs can change significantly when gases and bio-molecules are adsorbed to their surface. These changes can be detected in resistor, transistor, or capacitor devices. A principle advantage of TFT SWNT sensors in particular is that they respond to analyte surface coverage, as opposed to conventional sensors, which respond to analyte concentration. SWNT TFT sensors are thus well-suited for detecting chemical weapons agents and explosives, which typically occur in low concentrations *in situ*.



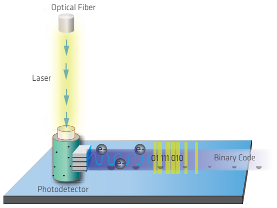
High-Frequency Devices

High-frequency devices offer great promise for the telecommunications industry. An 80 GHz CNT-FET made with semiconducting SWNTs was reported, illustrating the promise of our materials for this application. (Nougaret, L., et al., *Applied Physics Letters* (2009) 94, 243505.)



Drug Delivery and Detection

Semiconducting CNTs may prove useful for targeted drug delivery (estimated to become an $80.2B industry by 2014). Anti-cancer drugs may be delivered more efficaciously and with fewer systemic side-effects using a "smart" nanotechnology platform than by conventional methods. Small-diameter semiconducting SWNTs represent one such promising platform, due to their strong absorbance in the so-called therapeutic infrared window (between 700-1100 nm, depending on body tissue type).



Optical Devices

Photonic devices—such as saturable absorbers—are used as optical switches, optical amplifier noise-suppressors, optical limiters, and mode lockers for producing ultra-short laser pulses. These devices are widely used for optical communications, spectroscopy, and precision surgery (e.g. medical lasing). Materials which exhibit strong nonlinear electro-optical behaviors are required for most photonic applications. Ideally, these materials should exhibit fast response times, absorb over a broad wavelength range, and exhibit low optical loss. Our IsoNanotubes-S are one of a handful of materials in existence which satisfy these property requirements.

Company

About the company

"In October 2006, Professor Mark Hersam's research group at Northwestern University published a ground breaking paper in *Nature Nanotechnology* describing a process to sort CNTs by electronic structure. Shortly after publication, the research group was flooded with sample requests from around the world. Professor Hersam identified this opportunity and sought investors and entrepreneurs to commercialize this important technology. NanoIntegris was founded in January 2007. Three years later, NanoIntegris has dramatically scaled up production capacity and lowered costs to meet broad and growing global demand for high performance nanomaterials. Today, NanoIntegris supplies materials to over 100 organizations ranging from prestigious university research groups to Fortune 100 companies from around the world."

NORTHWESTERN UNIVERSITY

Mark Hersam - Co-Founder

Professor Mark Hersam is a founder of NanoIntegris and serves as the primary technical advisor. He is currently a Professor of Materials Science and Engineering and a Professor of Chemistry at Northwestern University. He earned a B.S. in Electrical Engineering from the University of Illinois at Urbana-Champaign (UIUC) in 1996, M.Phil. in Physics from the University of Cambridge in 1997, and a Ph.D. in Electrical Engineering from UIUC in 2000. In 1999, he also performed research at the IBM T. J. Watson Research Laboratory under the support of an IBM Distinguished Fellowship. Professor Hersam's research interests include single molecule chemistry, nanofabrication, scanning probe microscopy, semiconductor surfaces, and carbon nanomaterials. As a faculty member, Professor Hersam has received several awards including the Beckman Young Investigator Award (2001), NSF CAREER Award (2001), ARO Young Investigator Award (2005), ONR Young Investigator Award (2005), Sloan Research Fellowship (2005), Presidential Early Career Award for Scientists and Engineers (2005), TMS Robert Lansing Hardy Award (2006), AVS Peter Mark Award (2006), and two Teacher of the Year Awards (2003, 2007).
In recognition of his early career accomplishments, he was directly promoted from assistant professor to full professor with tenure in 2006.

Jean Pfau

Co-Founder and Board Observer

Mr. Jean Pfau is a founder of NanoIntegris, and advises the board of directors. Mr. Pfau began his career as a researcher at Charmilles Technologies, where he pioneered the field of electro-erosion machinery and became Head of Research & Development. He was instrumental in establishing Charmilles as the world leader in this technology market and served as the company's CEO during the 1970s and early 1980s. He recently retired as chairman of Swissquote in 2002, the Swiss market leader in on-line banking, a company which he guided from its founding in 1992 to its IPO in 2000 During the 1970s and 1980s, Mr. Pfau served as a Member of the Council of the Swiss National Bank and as Vice-President of the Swiss Machine Association. Mr. Pfau received a 'License en physiques' from the University of Geneva.

Philippe Inagaki

Co-Founder

Mr. Philippe Inagaki is a founder of NanoIntegris and serves as the chairman on the board of directors. Mr. Inagaki is also a founder and CEO of Polyera Corporation. Prior to founding Polyera, Mr. Inagaki worked in operations and business development roles at high-tech start-ups in a variety of fields including biomaterials and embedded electronics. He has also led technology scouting and investment efforts in universities across the US, and has given guest lectures on Entrepreneurship at Northwestern's Kellogg School of Management. Mr. Inagaki holds an A.B. in Physics *magna cum laude* from Princeton University where he received the Allen Goodrich Shenstone Prize for excellence in research.

Dan Leven

CEO

At NanoIntegris, Dan Leven manages long-term technical and business development, intellectual property development, and day-to-day operations.
He reports to the company's Board of Directors. Before joining NanoIntegris as Business Development Manager in February 2007, Mr. Leven was employed as Operations Manager at The Kisco Group, Inc., a NY-based Internet marketing company that develops content and software for consumer-information websites. During his tenure at the Kisco Group, Mr. Leven managed a team which devised strategies to optimally monetize the company's numerous web properties. Due in part to his efforts, Mr. Leven's business unit grew from zero revenue to full profitability in approximately one year. Mr. Leven received a BA in philosophy from Princeton University.

Nathan Yoder, Ph.D.

Product Development Manager

Dr. Nathan Yoder leads R&D and manufacturing for NanoIntegris. Over the last two years, Dr. Yoder has been responsible for a 10,000X increase in production capacity, as well as continued material optimization and new product development.
Dr. Yoder received a B.S. in Materials Science & Engineering from Purdue University and a Ph.D. in Materials Science & Engineering from Northwestern University. During his academic career, Dr. Yoder researched topics related to nanotechnology, molecular electronics, and scanning tunneling microscopy. His work has been published in *Physical Review Letters*, the *Journal of the American Chemical Society*, and the *Proceedings of the National Academy of Sciences*. He also holds a Visiting Scholar position at Northwestern University.

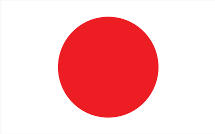
Elliott Garlock

Sales and Marketing Manager

Elliott Garlock leads commercial activities at NanoIntegris by establishing and developing relationships with companies, national labs, and academic research groups from around the world. Prior to joining NanoIntegris, Mr. Garlock was a marketer at Procter and Gamble in Cincinnati, Ohio. Prior to his tenure at Procter and Gamble, Mr. Garlock served as president and board member of Student Agencies, Inc. (a $2M student services company in Ithaca, New York). Mr. Garlock was responsible for business operations of seven divisions employing 200 employees. During his tenure, corporate revenue increased by 14% and gross profit increased by 9%. Mr. Garlock received a B.S. from Cornell University.

NanoIntegris

Distributors (Japan)



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