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Nanotechnology E4090 HW #7 Assignment – Viability Analysis of Unidym

Acquired in June 2006 as a majority-owned subsidiary of Arrowhead Research (NASDAQ:ARWR) through another fully-owned subsidiary, Nanopolaris, Unidym is a spin-off company seeking to apply the novel properties of Cabron Nanotubes (CNT's) to a wide range of traditional electronics. Their product line is divided into three segments, each related to a well-established market where CNT's could prospectively offer significant advantages: transparent electrodes, thin film transistors, and fuel cells. Adapting the products of academic research into the synthesis, processing, and deposition of CNT's, the company hopes to scale contemporary advances in nanoscale materials into the manufacturing processes that define the multi-billion dollar electronics and energy storage markets. This report will provide a brief assessment of their proposed technologies, contextualize them within the emerging research environment, and advise whether private equity investment is advisable to produce a return on investment within a five-year term.

At their best, CNT's represent a unique combination of properties seemingly ideally suited for the nanoelectrician: their metallic formulation offers ballistic transport; each component has a well-defined uniform nanoscale thickness and a controllable length that can extend to an aspect ratio on the order of thousands; tubes have a robust rigidity that gives not only mechanical support but the simple linearity that fits the current paradigm of circuit design. In application, however, they have represented a profound disappointment. Despite years of refinement, all synthesis techniques continue to have the same maddening result of producing a weighted, stochastic mix of character in the resulting CNT's; the best utile approaches so far are post-processing that rely on sorting out[1] or destroying tubes[2,3] of the unintended form thus resulting in an unacceptably poor yield. Even with an ideal source for CNT's, integration represents a terrific obstacle. *In situ* growth, the ideal option – and an ability assumed for Si-based surface and bulk micromaching – has yet to be advanced beyond select modes of surface-perpendicular growth of CNT's on Si[4,5]. Demonstrations relying on nanoprobes[6,7], electrophoresis[8], microfluidics[9], and biochemical direction[10] have been inspirational but remain far from anything potentially useful in large-scale manufacturing.

Unidym's technical portfolio is represented by the works of several prominent researchers supported by a similarly eminent advisory committee. Descriptions of their intellectual property holdings are vaguely described as relating to "Compositions of Matter", "CNT Production", "CNT Processing", and "CNT Applications" but it is far more useful to look at the work of the attached researchers as drawn from official company registration and various press releases from

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[1] Michael S. Arnold, Alexander A. Green, James F. Hulvat, Samuel I. Stupp, and Mark C. Hersam. Nature Nanotechnology 1, 60 - 65 (2006)
[2] Philip G. Collins, Michael S. Arnold, Phaedon Avouris. Science, 292, 5517, 706 - 709 (2001)
[3] http://www.youtube.com/watch?v=Rxmm0q3PklQ&NR=1
[4] Bingqing Wei, Z. J. Zhang, G. Ramanath, and P. M. Ajayan, Applied Physics Letters, 77, 19, (2000)
[5] Ant Ural, Yiming Li, and Hongjie Dai, Applied Physics Letters, 81, 18, 28 (2002)
[6] Toshio Fukada, Fumihito Arai, Lixin Dong, Proceedings of the IEEE, 91, 11 (2003)
[7] http://www.youtube.com/watch?v=r1ebzezSV6s&feature=related
[8] Kunitoshi Yamamoto, Seiji Akita, Yoshikazu Nakayama. J. Phys. D: Appl. Phys. 31 8 (1998)
[9] Jang-Ung Park, Matthew. A. Meitl, Seung-Hyun Hur, Monica L. Usrey, Michael S. Strano, Paul J. A. Kenis, and John A. Rogers. Angew. Chem. Int. Ed. 2006, 45, 581 –585 (2006)
[10] Kinneret Keren, Rotem S. Berman, Evgeny Buchstab, Uri Sivan, Erez Braun. Science, 302, 5649, 1380 - 1382 (2003)

Unidym and their parent company, Arrowhead Research. The foundational researcher is the CTO, Dr. George Grüner[11], a professor at UCLA who has assorted experience in CNT synthesis and processing techniques. His work is complimented by that of Dr. Jie Liu[12], a professor at Duke whose contributions focus on the use of CNT's as electrical interconnects, and Prof. Andrew Rinzler[13] at the University of Florida who has been a strong proponent of the integration of CNT's into flexible, transparent films[14]. Also of note in an advisory role is Professor John Rogers, a UIUC researcher who has been particularly effective in demonstrating possible applications of CNT's to practical and scalable electronics. Surprisingly, no patents could be traced directly to either Undiym or Arrowhead which implies that their IP is all under license from individual holders or held by a shelter company; either way, their actionable portfolio remains frustratingly obscure. Another convoluting factor is that these same researchers are active participants, if not founders, in *de facto* rival companies. Given the nominal concrete information released by the company, it is very difficult to discern what can be expected from their promised technologies.

Without the public release of specific information regarding the scientific basis for their technologies, the best opportunity available is extrapolating from the publications of the associated researchers. Unfortunately, this is problematic in terms of applicability and ownership. Even assuming that peer-review guaranteed the published results – a huge presumption – the publications in question have the typical academic scope of treating lab processes, entirely divorced from the scaled-up volume any successful manufacturing process would necessitate. Recreating results on this larger scale is an entirely disparate challenge and thus tempers the applicability of any report. Furthermore, there is ambiguity as to what share of their personal IP a researcher might have contributed to any given project. This report will thus focus primarily on the work of Professor Grüner, likely the most personally invested of the scientific team and holder of a broad portfolio of relevant technologies.

With this context in mind, the outlook for Unidym's three highlighted applications seems poor. The application of CNT's to flexible thin film transistors would require precision in patterning that is far beyond current abilities in addition to advances in synthesis that would allow for the economical scaling of manufacturing. Moreover, there is little impetus for the development of this technology given advances in polymers and advances such as ongoing work on patterned, single-crystal, flexible circuits, represented by companies such as Semprius. Interestingly enough, this spin-off is premised on the work of the same John Rogers who is an acting advisor for Unidym and combines his work on CNT-integration with the ground-breaking research on arbitrary, nanoscale patterning by Professor George Whitesides; together, their approach seems much more mature and promising than that suggested by Unidym through Grüner's papers[15][16][17][18].

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[11] http://www.unidym.com/company_3.html
[12] http://www.arrowheadresearch.com/sponsored5.html
[13] http://www.arrowheadresearch.com/sponsored6.html
[14] "New nanotube films have high potential for consumer, military applications" http://news.ufl.edu/2004/08/27/nanotubes/
[15] E. Artukovic, M. Kaempgen, D.S. Hecht, S. Roth, and G. Grüner, Nano Letters, 5 4, 2005
[16] David S. Hecht, Liangbing Hu, George Grüner, Current Applied Physics xxx (2005) xxx–xxx
[17] David Hecht, Liangbing Hu, and George Grünera, Applied Physics Letters, 89, 133112 200
[18] N. P. Armitagea, J.-C. P. Gabriel, G. Grüner, Journal of Applied Physics, 95, 6, 2004

Unidym's unelaborated plans for fuel cell technology are similarly inauspicious. Despite impressive proclamations that CNT-based electrodes can minimize inefficiencies in the function of fuel cells, there seems to be little technical backing for these claims; a review of their scientific consultants and related literature reveals no expert in fuel cell design or published substantiation of their claims. In fact, intuitively, it would seem disadvantageous to apply either a weave of CNT's directly as an electrode, as this would provide suboptimal contact area, or CNT's suspended within a film, as this intermediate matrix might mitigate the prospective advantages of CNT's. Regardless, there are obvious engineering challenges here which seem completely unaddressed by Unidym and their constituents.

The proposed use of CNT–based films as transparent electrodes is by far the most promising as it tolerates nonspecific synthesis and orientation. A randomly oriented network suspended within a flexible film provides the ideal electrical, optical, mechanical character for transparent and robust electrode for photonic applications. Critically, this is imagined as a replacement for ITO in LCD displays. The standard material within the burgeoning display market suffers from fragility, a complicated deposition process, and an unfortunate fundamental trade-off between optical transparency and conductivity. Most importantly, however, the search for an alternative technology is driven by the price of indium which has risen from an annual average of $97/kg in 2002 to $855/kg in 2006 with a peak of above $1000/kg[19]. As LCD displays have assumed a dominant role in the display market and their integration into mobile devices has continued to grow, demand for indium has grown dramatically and this perceived trend has driven up prices dramatically.

As a replacement technology, Unidym's CNT-films face significant competition other technologies such as doped ZnO, conductive organic polymers from firms such as AGFA, Baytron, and Eeonyx Corporation, and various other thin-film technologies announced by start-ups with varying levels of vagueness. Amongst the most prominent are another CNT-based solution from Eikos and whatever "nanostructured wet-coating" Angela Belcher has devised for Cambrios. Current reports seem to indicate that the conductivity achievable via organic polymers is simply insufficient for use as a display electrode, but the market will be in flux for years as it becomes clear which products might come to fruition.

A more profound question, however, is whether this market will ever exist at all. Though niche applications will always exist for alternative display technologies, it's unclear that there is a need to replace the incumbent ITO. The one truly distinctive advantage of CNT-based films is flexibility, a trait that industry has engineered current rigid displays without. Though fully flexible displays – archetypically imagined as electronic newspapers – may one day become a reality, this horizon is well beyond the current generation of technology, leaving cost as the motivating factor behind the replacement of ITO.

Which is problematic. Premising an entire R&D program on the high cost of a given material is a tremendous extension of the investor's risk; equity is now wagered on not only the success of research but trends in the mercantile market. The growing expense of indium may seem like a foregone conclusion given a superficial regard of market behaviour over the past few years – an eight-fold increase in four years is hard to argue with! – but the reality is actually an interwoven

[19] U.S. Geological Survey, Mineral Commodity Summaries, January 2007

story of stockpiling, uncertainty in the currency and export markets (mainly in China), and self-perpetuated waste. The irony of the indium market is that price increases have been largely under the control of manufacturers and processors who have had little incentive to improve low-yield ITO manufacturing processes or invest in recycling technologies[20]. As demand has increased, a phantom stress has emerged to the benefit of primary refiners but there has never been even a remote risk of shortage, "The world reserve base for indium is estimated to be about 5,700 t, which is far in excess of probable consumption over the next several decades; the United States has about 11 percent of this base. The sustainable production and consumption of indium appears to be no impediment in future years."[21] This implies that were a replacement technology to emerge with only its cost to recommend it, it could likely be undercut by a determined indium market. Indium is retrieved as a derivative of the zinc mining process so, fundamentally, the future viability of CNT-based technologies in the display sector is defined by the need of Zn compared to the demand for displays. Despite a recent dip in refinery activity, a contributing factor to high indium pricing, demand for zinc is expected to grow dramatically; coupled with the process refinements for indium that are waiting for the motivation to be implemented, the price of ITO would seem well-under control.

Ultimately, Unidym is a poor candidate for such a short term investment. There is little reason to expect any sort of viable product along any of its three concerns given the current state of research. That being said, any sort of fundamental discovery in terms of either the selective synthesis or patterned growth and deposition of CNT's would revolutionize what is possible and catapult forward an entire new generation of start-ups. It's nice to know that you'll always have a job.

[20] John D. Jorgenson and Micheal W. George, *Mineral Commodity Profile: Indium*, Open-File Report 2004-1300 for the U.S. Department of the Interior and U.S. Geological Survey.
[21] Ibid.