Architectural Innovations in Perspective

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Introduction

Departing from the discussion in earlier chapters of innovation from within the existing value chain of the semiconductor industry, this chapter discusses examples of innovations in nanoelectronics that initially do not link-up with an existing value chain. All the examples discussed in this chapter combine the introduction of technological novelty with the creation of new networks of linkages. On the one hand novel technologies are introduced that radically depart from existing technological capability and skill sets. On the other hand, the formation of a new network of linkages is needed to create a new value chain providing market access. As such, the examples provide insight in the dynamics of *architectural innovation*, an innovative setting that corresponds to the upper right quadrant of the Abernathy and Clark framework (Abernathy and Clark, 1985).

One goal of this chapter is to create a greater awareness of the relevance of innovation in this context, despite the high level of uncertainty associated with such ventures. In the examples discussed, there are no clearly defined technological capabilities and no established rules for the competitive game like those in the existing microelectronics value chain. Specific strategies for product development, manufacturing and commercialisation have therefore to be developed and

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have to be continuously redefined to adapt to changing circumstances. As a result, there is a large variety of innovation pathways shaped by the actors involved and by the specific characteristics of the selection environment — in particular the linkages that can be build with business partners and customers in due course.. Although the unpredictability of innovation in this context implies a high level of risk and volatility, the promise of future returns justifies the necessary investments and motivates entrepreneurs to take up the associated challenges.

As this study underscores, the dynamics of technological convergence, but also technological branching, is a source of new technological options opening up opportunities for revolutionary and radical innovation. In this chapter, MEMS (Micro Electro-Mechanical Systems) technology was selected as an exemplary technology in the nanoelectronics field to illustrate this dynamics of technological change and innovation associated with convergence and branching. The focus on MEMS as one example of a nanoelectronics technology makes it possible to illustrate the wide variety in value creation activities, innovation pathways and emerging value chain structures that emerge as a reflection of the introduction of a limited but shared set of technological capabilities. The four examples that constitute the core of this chapter take the perspective of entrepreneurial firms developing novel MEMS and micromachining technologies for applications outside the existing value chain through a combination of technological capabilities in semiconductor and MEMS manufacturing. Despite the differences between the examples, a discussion of the examples allows for the identification of some factors that are essential to successfully innovate in an architectural setting. These factors are then used to formulate recommendations for business and policy actors interested in architectural innovation in nanoelectronics.

MEMS and micromachining: segments in the electronic devices industry

Manufacturers of MEMS and micromachining based devices employ semiconductor microfabrication technologies to take advantage of the mechanical properties of silicon rather than (or in addition to) its electrical properties. Examples of MEMS based devices are for instance DNA-chips (e.g. Affymetrix), electrostatic sensors (e.g. Analog Devices), inkjet heads (e.g. HP and Canon), hard disk heads (e.g. Seagate) and microsieve-based inhalers (e.g. Medspray). Since MEMS devices were first introduced in the 1980s, the field has basically evolved disjunctive from the semiconductor sector, and MEMS were not considered a key element for the semiconductor industry. Nevertheless, there was a mutual influence and value exchange, for example through equipment manufacturers such as ASMI that were active in both fields.

Since its conception, companies operating in the microsystems field have faced the challenge how to expand and speed-up business development in a very fragmented industry and without a significant level of product standardisation (through, for instance, a dominant design or unit cell). The current dynamics in the MEMS field can be characterised by the following statement: Every product requires its own unique technology platform, package technique and testing procedure (Eijkel et al., 2005). Although some application-specific dominant technology-product paradigms have become established, there is no industry-wide standard for packaging designs as yet, as opposed to, for instance, the situation in CMOS electronics. This has to do with the fact that the functionality of a MEMS device is generally based on specific hardware settings (e.g. constructions and materials), whereas functionalities in digital integrated circuits are basically ‘software-programmable’, either through circuit design or through today’s programmable device concepts. This specific character of the MEMS field provides an extra barrier to standardisation, large-scale infrastructure development and cross-industry learning.

New developments, as presented in previous chapters, show that lately attempts are made to integrate MEMS and micromaching-based devices with electronic device technologies in one single package, using a System-in-Package (SiP) approach. After a decade of separate evolution, MEMS technologies are now recombined with other semiconductor technologies and thus become part of the nanoelectronic palette. One example is the HUMAN++ concept described in Van Hoof’s contribution ‘More than Moore and Heterogeneous Integration’. Figure 1 schematically depicts branching and convergence in the developmentof semiconductor-related technological capabilities and skills: on the one hand towards incremental innovation in the electronic devices industry that manufactures integrated circuits and on the other hand branching of towards the MEMS sector that emerged in the 1980’s. Since a couple of years, developments in MEMS have started to converge with developments in CMOS IC technology through for instance the introduction of System-in-Package product designs. (The concepts of a virtuous cycle and a disruptive cycle presented in

Figure 1 are further worked out in the paragraph 'Architectural innovations and actors in the disruptive cycle' of this chapter.)

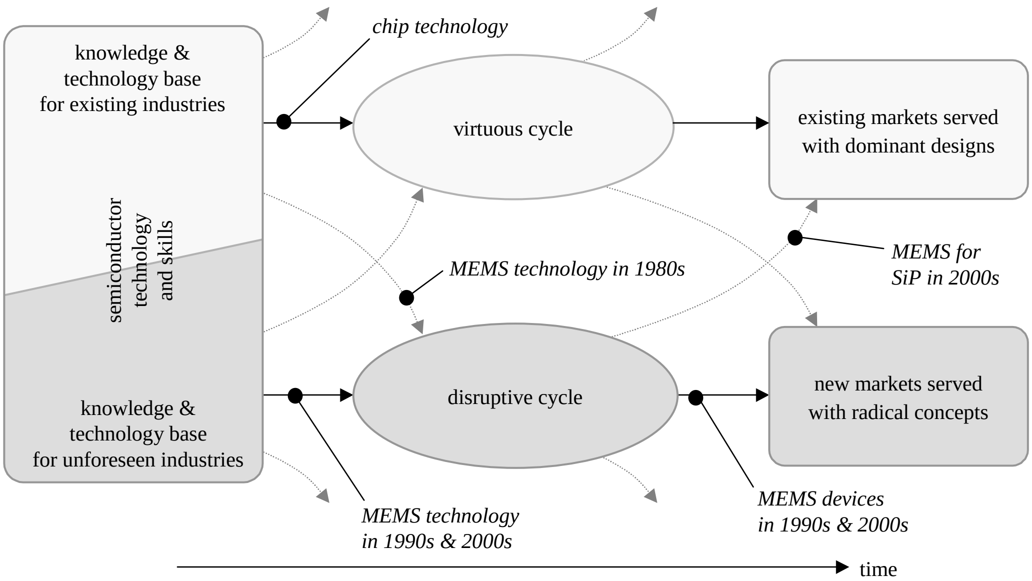

Figure 1: Semiconductor technology and skills creating and serving different branches

Examples of architectural innovation

Texas Instruments - Digital light processing

Texas Instruments is a high-tech, multinational firm active in a multitude of markets with its solutions based on digital signal processing and analogue (semiconductor) technologies. Texas Instruments is an example of an industry leading firm studying new technology and applying it, not only to improve existing product-market combinations but also in order to 'parachute' the technology into new markets.

The Digital Light Processing (DLP) division, initially called the Digital Micromirror Device Project Division, was set-up by dr. Hornbeck, now a vice-president of Texas Instruments Within Texas Instruments, the Digital Micromirror Device project occurred as a result of investigating the convergence of MEMS and semiconductor microfabrication technology. The resulting DLP technology uses an all-digital chip to project and display images (e.g. Hornbeck, 1996; Texas

Instrument, 2006). This chip consists of a CMOS logical device on top of which a rectangular array of up to a million hinged, microscopic mirrors is mounted (Figure 2). In a DLP projection system, red, green and blue lights are alternately flashed onto the mirrors, which switch on and off in response to a video signal fed into the chip. The mirrors can switch at a rate of up to 5,000 times per second. The light they reflect is directed through a lens onto the screen creating an image.

Today, DLP technology is considered to be the single largest success story in the MEMS field as it was first introduced in a large range of media projection applications and moer recently in display applications. These include business projectors, home cinema applications, professional video walls (for example, command and control centres used by telecommunications and utility companies), commercial entertainment applications (for instance, concerts, award ceremonies and casinos) and applications that require the ability to quickly, easily and accurately modulate light.

Despite this successful outcome, the DLP division was nearly eliminated a number of times since its inception. Just like many other product offerings based on newly introduced technology, the initial product that was developed did not provide the value that had become expected by Texas Instruments. However, the second and third product generation based on this technology have fared far better, although the innovation journey for these products also knew some bumps.

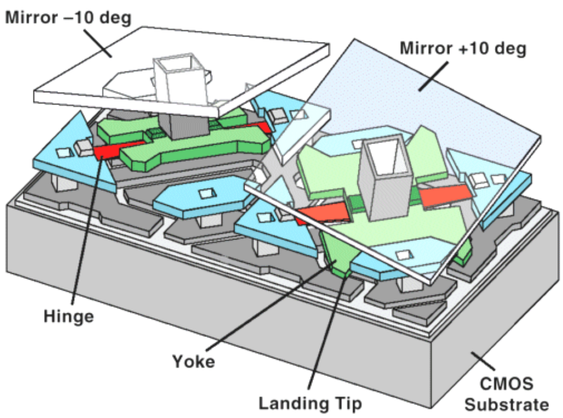

Figure 2: Overview of a DLP, a Digital Light Processing device (Texas Instruments, 2006)

This technology was a novelty, not only for Texas Instruments but also for the existing projection and display businesses. As the DLP system substitutes traditional display and projection technologies, Texas Instruments had to compete directly with firms in this sector. For them the

DLP system formed a radical departure from their traditional product concepts. In addition, the technological capabilities required to produce a DLP system bear no resemblance to those required for the manufacturing of traditional projection or display systems. The radically novel character of the new product concept was a source of problems, but it also gave Texas Instruments the time it needed to probe the market and learn about customer needs, while their competitors were stuck in the 'old' technology-product paradigm. While Texas Instruments focussed on the development of their DLP system, their competitors' response was to accelerate the learning in their traditional technology lifecycles. But as Texas Instruments found out, a product driven by a radical technology may not enjoy instant commercial success, even if it performs much better, is more reliable and is much cheaper than existing products. The company faced problems when trying to engage designers of projection and display systems in design activities. Further, Texas Instruments had to overcome production problems resulting in considerable cost overruns (some say billions of dollars) that were needed to overcome manufacturing problems. But through perseverance the DLP division developed into a more than $1 billion business.

The DLP device can be seen as an architectural innovation (Abernathy and Clark, 1985): A combination of new and existing knowledge of display systems, MEMS and semiconductor technologies has made possible the development of a complete new device that allowed Texas Instruments to enter a completely new markets. To be successful, existing value chain structures had to be severely challenged. Traditionally, the cinema (projector) business has been based on analogue content and equipment. In this fragmented business, the introduction of digital content and digital equipment was extremely important for the success of DLP systems. Further, the continued financial and strategic backing that Texas Instruments has provided at the highest level to the DLP initiative has been essential for the fledging division to learn and to cross the chasm (see the paragraph 'Architectural innovations and actors in the disruptive cycle'). Mr. Hornbeck's vision and drive to overcome internal barriers within Texas Instruments has allowed those resources to continue. It is exceptional that a large firm like Texas Instruments initiates large scale investments for architectural innovation developments. But the initiative has survived the disruptive cycle (see the paragraph 'Architectural innovations and actors in the disruptive cycle') and DLP systems became firmly established in its markets and can now be considered a mature technology. The entrepreneurial activities in new technology and market areas and the perseverance on a multitude of aspects have resulted in a successful DLP division.

i-STAT – Microfabricated biosensor chips

The company i-STAT Corporation — founded in the early 1980s — develops biosensor chip technologies in order to create point-of-care-diagnostics systems. These biosensors are used in light-weight, handheld bedside readers and a variety of single-use, disposable cartridges. With the micromachined sensors these systems can measure the level of care-critical blood parameters (e.g. sodium, potassium, chloride ions, glucose) in very small (60 µl) blood samples (Figure 3 and produces results in about two minutes (instead of a day or more when samples are sent to a laboratory). The concept revolutionises the value chain of health care diagnostics and treatment. A variety of cartridges is available for the measurement of dozens of blood parameters. i-STAT, the first company to make biosensors using semiconductor wafer technology, now annually produces and ships tens of millions of these biosensor devices.

Glenn Baeske/Huntsville Times

The tiny disposable part of the i-STAT helps nurses and doctors diagnose and assist more quickly than routine lab work.

Figure 3: Disposable cartridges (i-STAT, 2006)

i-STAT entered into a strategic alliance with Abbott Laboratories for point-of-care testing in 1998. The agreement included marketing and distribution agreements and a stock purchase agreement, along with research and development and license agreements for certain new diagnostic products. Abbott Laboratories is a more than a century old pharmaceutical, nutriceutical and diagnostics company with worldwide sales of more than $22 billion with and earnings of $3.4 billion in 2005. Abott Laboratories acquisition based growth made it today's leader in point-of-care diagnostics with an outstanding market channel in the medical field. Thruogh this deal i-STAT got the market access to expand its business at a low risk. But in 2002, the company announced its intention to end its deal with Abbott Laboratories. i-STAT was to pay tens of millions of dollars as a termination fee and return payment. The initial investments of Abbott Laboratories in i-STAT did not continue.

Then, in 2003, Abbott Laboratories (Abbott Laboratories, 2003) agreed to acquire the shares of i-STAT it did not already own for a net transaction value of approximately $392 million. Yet — as shown above — just a little while earlier Abbott Laboratories disinvested in i-STAT. Abbott Laboratories, which had had internal discussions regarding the utility of point-of-use care, now stated that i-STAT *".. provides an excellent fit with our long-term strategy of expanding our capabilities in diagnostics while targeting medical needs at the point of patient care*." Contrary to its earlier intention, the chairman of the Board of i-STAT said: *"Abbott is the ideal fit for i-STAT. Our leading technology complements Abbott's broad capabilities in the worldwide diagnostics market*."

For a firm like Abbott — strongly linked to the virtuous cycle (see paragraph 'Architectural innovations and actors in the disruptive cycle') — it is hard to fully oversee the potentials, implications and cannibalising effects of acquiring innovative small firms that offer architectural innovations and therefore operate in a disruptive innovation cycle (see paragraph 'Architectural innovations and actors in the disruptive cycle'). Whether to invest or disinvest in such firms is a question that has to be continuously re-evaluated by the incumbent. In the end, Abbott Laboratories strategically decided to let the i-STAT concept, together with other (to be) acquired concepts, be part of Abbott's expanding product and services portfolio. In terms of the framework of Abernathy and Clark (1985), i-STAT created an architectural innovation that in due time evolved into a niche innovation and even a next generation regular innovation as its biosensor-based point-of-care-diagnostics systems were successfully adopted in the market. The implications of its system for health care diagnostics have been fundamental.

The case further shows that partnering offers good possibilities for a small company to move through the above-mentioned innovation path from architectural to niche to regular innovation. Such a partner can provide the capital necessary for investment in research and development, marketing support and, above all, a distribution channel. Nevertheless, investing partners such as Abbott Laboratories also continuously evaluate their strategic agendas. Innovative concepts such as the i-STAT system make them aware they need to balance interests over the years: to monitor and support high-tech entrepreneurial companies that develop interesting architectural innovations or to expand their existing products and service portfolio via the acquisition of those companies with the risk of losing entrepreneurial mindsets in these organisations

Micronit Microfluidics - Glass chip technology

The Dutch technology platform company Micronit Microfluidics designs, simulates, prototypes, develops and manufactures custom-made glass and silicon microfluidic chips for detection purposes (contact-based, contact-less conductivity, amperometric detection) and laboratory purposes (mixing, reaction, heating or electrophoresis analysis) (MicroNews, 2004; figure 4). Applications for its chips and microfluidics systems include capillary electrophoresis, blood analysis, DNA analysis, micropipettes for clamping DNA molecules and microneedles for painless blood collection and drug delivery (Micronit Microfluidics, 2006; MicroNews, 2004). Microfluidics is a multidisciplinary science and technology domain that studies and applies the behaviour of fluids at microscale and mesoscale, combining physics, chemistry, engineering and biotechnology. The results of Micorfluidics are used in the development of a broad variety of devices and systems, such as DNA microarray technology, lab-on-a-chip technologies, pneumatic microvalves, chemical microreactors, microdispersers, printheads and microthermal and micropropulsion concepts.

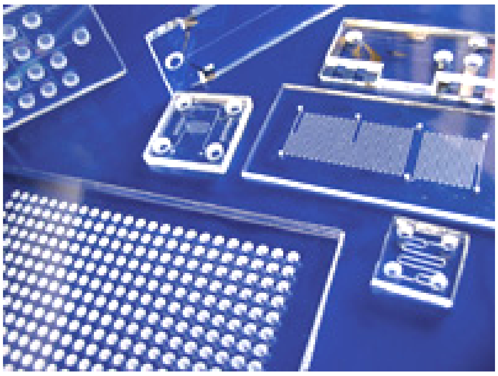

Figure 4: Overview of glass chip devices (Micronit Microfluidics, 2006)

The privately held company was founded in 2001 by a team of young entrepreneurs. Today, it employs 20 persons in R&D, production and marketing & sales (Q1, 2006). The company's production capabilities were recently upscaled. Over the years, it has operated in close cooperation with the MESA+ research institute of the University of Twente (research on materials, micromaching, microelectronics, microsystems and nanosystems) and technology and business partners. This cooperation has a complementary character as to research, technology and business. Micronit Microfluidics utilises several micromachining-related technologies, such as micropowder blasting, metal sputtering, advanced etching techniques (hydrofluoric acid etching, heated potassium hydroxide etching and deep reactive ion etching), electrodes integration and substrate bonding. Due to its being embedded in research and business networks, both locally and internationally, Micronit Microfluidics appears to be able to attract and develop relevant knowledge and competences so as to upgrade its technology platform portfolio and to expand its business and revenue positions.

Knowledge and technologies, appropriate connections with partners and, above all, an entrepreneurial mindset of a small company have created abilities to revolutionise cost-effective and flexible detection and laboratory functionalities in life sciences, pharmaceutical and chemical industries. It might be interesting to see in what way Micronit Microfluidics will be able to expand strategic partnerships in order to stimulate its worldwide positions in existing and new value chains so as to create market access for its microfluidics and lab-on-a-chip functionalities.

Micronit Microfluidics combines semiconductor and micromaching technologies can to manufacture customised glass microfluidic chips and lab-on-a-chip devices that are used in various non-electronic industries. At the moment, and in connection with the Abernathy and Clark framework (Abernathy and Clark, 1985), niche and architectural innovation movements can be observed: A combination of new and existing semiconductor knowledge and technologies enables the development of technology-product platforms that address specific niche segments in fields that are not addressed by the electronic devices business. Similar innovation settings are applicable to the microarrays of Affymetrix based on semiconductor manufacturing techniques and glass chip technology, Medspray’s aerosol technology for drug delivery based on microlithography processes and microsieve technology and Ford’s micromachined silicon fuel injector nozzle with highly uniform and rectangular orifices. In the future, as microfluidics technologies addresseing specific industry segments become more mature, the innovation dynamics can be expected to become of a more regular nature. Unless, of course, new (radical) technologies, competencies, actor linkages and entrepreneurial ambitions activate or reactivate niche and architectural innovation movements.

This example shows that technologies commonly used in or connected with the semiconductor industry make radical technology and innovation developments possible in other industries. Micronit Microfluidics operates in a very entrepreneurial way. It pushes its new technology to newly emerging market segments in a process of architectural innovation, at the same time attempting to make it a next generation of detection and laboratory functionalities part of more regular innovation setting.

Zyvex - From microassembly technology to molecularly precise manufacturing

Zyvex Corporation is an ambitious high-tech small firm operating in the United States. It was founded by Mr James Von Ehr II in 1997 and employs more than 60 persons (Q1, 2006). Its vision is to become the worldwide leading supplier of tools, products and services that make adaptable, affordable and molecularly precise manufacturing possible. Parallels can be seen with Ford Motor Company in its early days: Not being the inventor of technology but rather the innovator that has a vision of the future of an industry (Walsh, 2004; Thukral et al., 2006). This could be linked to an architectural innovation vision potentially becoming a regular innovation setting (Abernathy and Clark, 1985). In connection with its vision, the high-tech company focuses on a rapid transformation of its scientific breakthroughs into commercial applications and licensing opportunities in the fields of materials, tools, and structures. It sees relevant markets in aerospace, defence, health care, medical applications, the semiconductor industry and in telecommunications. The company and its key employees are embedded in a variety of academic, business and governmental policy networks. Zyvex has utilised government research funding through US agencies, such as NIST-ATP (National Institute of Standards and Technology — Advanced Technology Program).

The stated ambition of Zyvex Corporation provides the organisation with a strong long-term orientation, reflected in a drive to build up a strategic portfolio of breakthrough competencies. In this approach, the company tries to profit from its developing competencies while concurrently focusing on its long term objectives. The financing structure of the company makes this combination of short-term and long-term positioning possible: So-called 'patient money' is provided by individuals that are closely involved with the firm. This differs from a financing structure based on traditional venture capital, where strong revenue results are expected to be attainable by the rapid introduction of new product-market combinations.

Although the competencies required to support Zyvex's ambition of molecularly precise manufacturing are still under development, concrete products were already commercially introduced. The company has developed products in the fields of microassembly (e.g. MEMS grippers, automated microassembly concepts), nanomanipulation (such as nanomanipulators for studying and testing nanostructured materials and probe advanced semiconductor chips) and nanomaterials (for instance, the functionalisation and processing of nanotubes). The company is able to build component-based three-dimensional structures and devices (Figure 5). By using proprietary MEMS and NEMS (nano-electro-mechanical systems) libraries of end-effectors, handles, connectors and sockets, Zyvex routinely achieves high positional accuracies for a large number of components in automated processes. The technology is suitable for applications such as high-precision alignment, high-precision automated mechanical assembly and other industrial applications, where high-precision assembly is desirable (see e.g. Tsui et al., 2004; Sarkar, 2005). One of the opportunities pursued by Zyvex is the development and commercialisation of tools specifically aimed at the bio, medical, pharmaceutical industries.

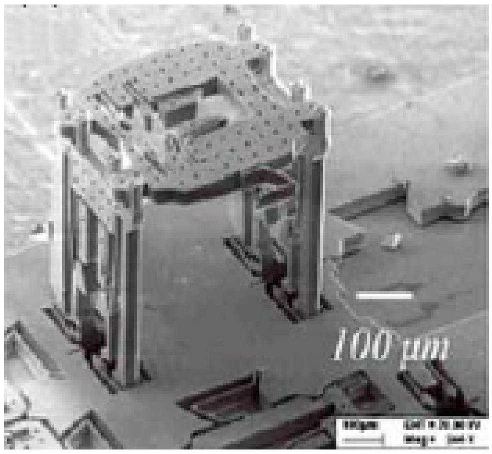

Figure 5: Overview of microassembled structure (Zyvex Corporation, 2006)

Zyvex Corporation needs to continuously learn about the value of its competencies in order to be better able to position its technologies and solutions in the market. Therefore, the firm wants to provide solutions for actual customer needs from the beginning. The formation of partnerships is one way to build this understanding. Zyvex thoroughly reviews its partnership opportunities and rejects nearly 90% of these as not having a strategic alignment and corporate stretch (Walsh, 2004a). The company differentiates potential partners in sectors, such as knowledge and technology intermediaries and suppliers like Johns Hopkins, equipment manufacturers such as Becton Dickinson, market channel giants, such as Johnson, and Johnson and others (Walsh, 2004a). The company is also tentatively negotiating with large health care providers.

Zyvex Corporation is a long-term vision-driven innovator combining long term platform and product development with short term commercialisation aspirations. It is one of the very few true nanotechnology firms that are actually able to sell nanotechnology based products and to build strategic partnerships with partners that move in tandem with their own strategic intent. Zyvex actually commercialises enabling technologies that have the potential to become disruptive.

The question is how Zyvex Corporation will be able to simultaneously invest in and focus on *exploration* - needed to build its long-term oriented portfolio of competencies - and *exploitation* - keeping track of short-term customer needs, to learn, to adapt and to generate cash flow. With respect to the framework of Abernathy and Clark (1985), Zyvex intends to develop and introduce architectural innovations. On the other hand the company needs to build partnerships in order to create access to markets and in an attempt to shift existing customer needs, oriented at the products produced in a regular innovation context – towards the more radical innovations they intend to develop themselves, In this setting it is imaginable that an IPO (initial public offering) affects the short-term/long-term balancing activities of Zyvex Corporation.

The example of Zyvex illustrates that the ambitious focus on molecularly precise manufacturing gives Zyvex Corporation, as a high-tech small firm with appropriate financial and partnering positions, interesting possibilities to potentially revolutionise industries.

Elecsci - Embedded electron charge technology

The start-up Elecsci Corporation — founded in the USA in 2004 — develops a platform technology of engineered electronic materials that 'harnesses' energy from the surrounding environment due to principles of embedded electron charges (EEC; trapped electronics) in materials (Elecsci Corporation, 2005). EEC is a phenomenon where electrons become permanently trapped at the interface of certain layered insulator materials, resulting in a relatively permanent charge. Research performed at the Rochester Institute of Technology has provided the scientific and technological fundamentals for the start-up initiative. Its technology platform is based on standard CMOS manufacturing processes, which makes an integration of the material into silicon devices and low-cost, high-volume manufacturing possible. At the moment of writing, the Elecsci Corporation has an intellectual property portfolio of 9 issued patents and dozens of patent applications.

The company foresees devices in 'design families' related to standalone EEC applications, energy harvesters, sensors, actuators, RF MEMS and levitators (Figure 6). Its first applications will be energy harvesters and self-powered sensors for which there is a wealth of opportunities in multiple vertical markets, (for instance automotive, medical, consumer electronics and defence). Not only has this technology platform the opportunity to substitute technologies in existing products (such as accelerometers, microphones, bearings), but it can also be used in completely new applications, such as heel strike power generators or wall-hanging concepts based on electrostatic bonding. Apart from these innovative applications of EEC technology, the potential of Elecsci's technology is based the compatibility with CMOS manufacturing.

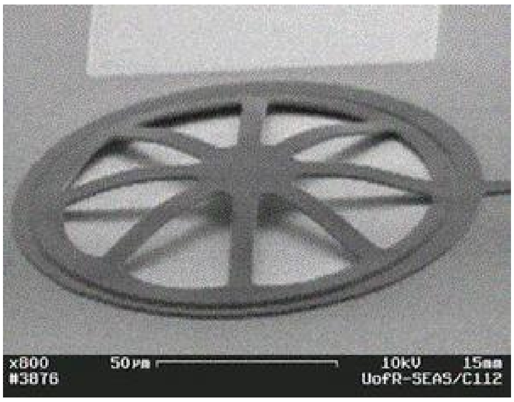

Figure 6: Micro-energy harvester device (Elecsci Corporation, 2006)

Elecsci expects that through this combination the technology could ignite new markets and bring about revolutions in a variety of existing markets. The disruptive cycle (see the paragraph 'Architectural innovations and actors in the disruptive cycle') can be recognised here. But the new and ambitious company has to work on finding ways to create and penetrate these potential markets for their 'energy, sensor and bonding concepts'. The creation of business alliances with existing companies that are already active in the targeted markets may be a way to create customer awareness and to identify early adopters of the technology. With regard to the innovation framework of (Abernathy and Clark, 1985), it could be interesting to see how Elecsci Corporation is going to position itself in existing value chains and business networks in order to make the step towards a more regular innovation setting (for example in the market for self-powered tire pressure sensors for the automotive industry or micro-pressure transducers for hearing aids). The start-up company with a radical technology portfolio that is now apparently focussed on innovation in a disruptive cycle could then become a platform provider that operates in the setting of a virtuous cycle. However, this orientation towards short term revenue generation could then be used to further invest in product-market propositions with a more radical character (for instance man-powered energy harvesters that can be integrated in shoes or bio-implantable energy harvester for neural stimulators or cardiac pacemakers). Referring to the framework of Abernathy and Clark (1985), this shows a tendency towards architectural innovation positions by serving or even co-building new value chains.

Architectural innovations & actors in the disruptive cycle

This paragraph will highlight architectural innovation activities seen from the perspective of the so-called disruptive cycle. Technology development follows an S-curve. Product adoption based on novel MEMS or semiconductor technology heavily relies on the 'lead user' (Von Hippel, 1986) and 'crossing the chasm' concepts (Moore, 1991). In the initial phase of technology development, early adopters will utilise a nearly completed solution while a direct benefit offsets reliability issues and any difficulty of use. In the next phase the product will be developed in order to 'cross the chasm' and meet the needs of early majority users. In this phase, it becomes clear whether or not the new technology-product paradigm has 'traction'. When the technology is ultimately accepted by the late majority and sceptics, it has made existing technologies obsolete. It slowly proves its full potential and becomes the new sustaining technology. The struggle for architectural innovations in the electronic devices industry to become mainstream by 'climbing' the S-curve is related to the above-mentioned process. Companies developing new, enabling technologies — for example i-STAT or Elecsci Corporation — transform or embed their new technologies in existing and emerging value chains so as to make the transition to a regular innovation regime. Strategic collaboration with partners within this emerging value chain is essential.

As stated earlier, architectural innovations located in the upper right quadrant in the framework of Abernathy and Clark (1985) represent a double challenge: implementing radically new technologies and operating in environments where new linkages have to be set up. There is another useful model that can used to conceptualise the differences in innovation setting of various enabling technologies. This model distinguishes between the so-called disruptive innovation cycle and the virtuous innovation cycle (Walsh and Kirchhoff, 2002; Walsh et al., 2004c; see figures 1 and 2). Architectural innovations can largely be related to the disruptive cycle.

Worldwide, thousands of high-tech small firms currently develop radical microtechnology and nanotechnology concepts with potential benefits directed at unarticulated customer needs. In this cycle, the key activities are creating and picking-up radical, enabling technologies, pushing them forward together with partners and through alliances, creating new cash flow, generating product-market combinations and stimulating their business positions. It appears that organisations with entrepreneurial drive and less organisational inertia are generally the most effective in crossing the chasm as they can operate in both newly created and existing value chains. See, for example, the cases of Zyvex and Micronit Microfluidics. This process is driven by high-tech entrepreneurship and intrapreneurship (e.g. Kassicieh et al., 2002). These forms of entrepreneurship are mostly related to small firms and start-ups, although the case of the DLP device shows that a vision-based entrepreneurial mindset can also be successful from within a multinational company, such as Texas Instruments. However, organisations that are already active in the virtuous cycle deal and work with sustaining technologies tend to focus on cost reduction through economies-of-scale and to listen to the needs of their existing customers. They therefore generally learn incrementally with regard to product design and manufacturing process design (Walsh and Kirchhoff, 2002; Walsh et al., 2004c; see figures 1 and 2). In the semiconductor sector, companies active in the virtuous cycle focus on the development of standard-based electronic devices, incorporating new — but not too radical — technologies that are suitable for high-volume production.

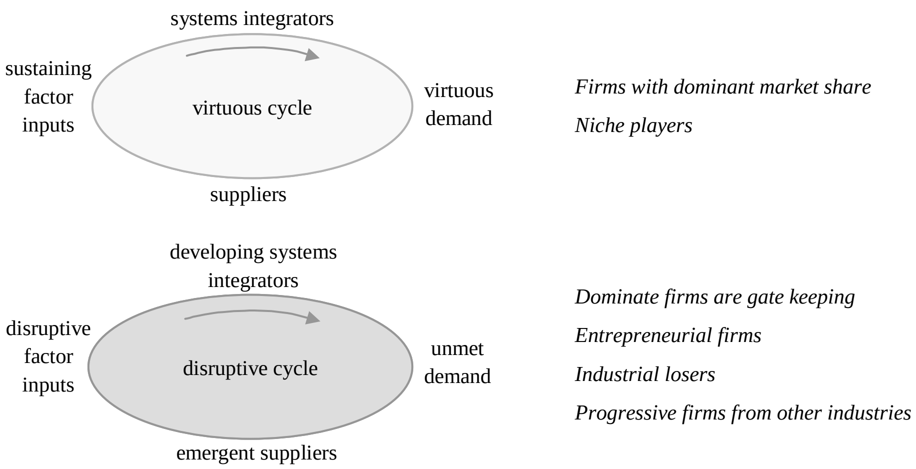

Figure 7: Aspects related to the virtuous cycle and to the disruptive cycle

The process of pushing forward semiconductor or MEMS technologies with yet unknown business implications by actors typically linked to a disruptive cycle can be characterised as ‘playing soccer in the fog’ even without knowing whether there is a soccer goal. The challenge is to instantly pick up and interpret signals and operate entrepreneurially in order to understand and develop the shape and position of the innovation playing field (see also Linton and Walsh, 2004). Roadmaps and scenarios play a role in this process (e.g. Walsh, 2004; Knol, 2004). Examples are NEXUS roadmaps and MANCEF roadmaps.

In such a disruptive cycle, actors can be identified with different roles and characteristics. The public knowledge institutes, such as universities, not only generate knowledge but also mediate between actors via transfer activities and commercialisation and spin-off programs. The cases Micronit Fluidics and Elecsci Corporation have shown how the involvement of academic research institutes can support technology and platform developments in small high-tech firms. Spin-offs operate as learning entities to generate added value with new knowledge and technologies. An ecosystem of companies and knowledge institutes can provide the entrepreneurial teams that lead spin-offs and start-ups with the proper interactions needed to co-develop and commercialise innovations.

The companies discussed in our case studies have different technology development and innovation characteristics. In general, various types of companies can be distinguished. We will briefly summarise them. One type of company is the so-called innovator with platform and product development and commercialisation aspirations. Companies, such as C2V, Lionix and Zyvex are examples of this category. Another type of company is the product company aiming at a few specific product-market combinations; examples are Gemidis, Affymetrix, i-STAT, Medspray, Microflown, Nantero and SiTime. The technology platform company attempts to broaden its range of product-market combinations using the same technology base in an attempt to serve multiple market segments. Micronit Microfluidics and Elecsci Corporation are examples of this category. A type of company with a more service oriented character is the foundry. It operates as a third party company to allow the development and production of specific (MEMS) devices, components or systems. Colibrys, Micralyne, HL Planar and HT Micro fit into this category. With regard to this typification, large firms such as Texas Instruments and Philips generally play multiple roles. Finally, a category for ‘other types of companies’ consists of facilitating companies, for example software specialists, business and technology consultants, IP and legal services, investment firms, etc. A disappearing type of company in the MEMS business is the engineering service provider focusing on concept developments for third parties. At the early stages of the MEMS industry, such service providers had some commercial success, but as the industry matured the added value of these companies evaporated because the by then established technology and product companies and foundries did not need this type of service anymore.

Discussion and final remarks

This chapter discusses examples of MEMS based developments to illustrate the dynamics of technological convergence and architectural innovation in the More than Moore domain. The MEMS field was chosen because, years after branching off from mainstream electronics, developments in the MEMS field recently started to converge with other fields in the More than Moore domain. The chapter describes examples of specific innovations that are based on MEMS technologies and require both the development of new technological capabilities and the the creation of a network of linkages to assure access to markets. In terms of the Abernathy & Clark framework, all these innovations started out in an architectural innovation setting , The examples thereby illustrate how promising innovation opportunities also exist outside existing value chains. For such innovative ideas to be successfully realised, an other mindset and environment are required than in an existing value chain. The next sections will discuss the lessons learned from these examples, in terms of the management of the innovating company, its ecosystem and the role of policy makers in shaping this ecosystem.

Implications for the company’s management

Architectural innovations on the move

Successful architectural innovations (upper right quadrant) will evolve towards regular innovation setting (lower left quadrant) over time in order to fully realise their promise of value creation and growth. Successful architectural innovations, often based on several compementary developments, then often ‘creatively destroy’ existing technologies, competencies and value chains (for example, Micronit Microfluidics and i-STAT’s point-of-care-diagnostics). Alternatively, an architectural innovation could also be transformed and absorbed by existing value chains (for example, Elecsci Corporation’s self-powered sensors for the automotive industry). This situation changes potential for value creation and growth of the architectural innovation. The challenge for the entrepreneurial team is to find ways to cross the chasm between early adopters and the early majority in a way that combines continuity (acquire capital, activate multiple-market strategies, serve launching customers, pick-up market feedback, generate early revenues) with a strong long-term vision of a clear radical value proposition in a nascent value chain. Long-term vision and perseverance are essential ingredients for such investments that require a combination of exploitative and explorative mindsets and activities (March, 1991) (for instance, the cases of Zyvex and Texas Instruments show an exceptional long-term vision and perseverance). Small, result-driven innovation steps in line with a long-term vision are essential for the entrepreneurial team to successfully realise the potential of an innovation idea, meeting the needs of internal and external stakeholders (such as investors, partners, customers and governmental policy makers).

Strategies to exploit architectural innovations

Companies addressing architectural innovations can use several (complementary) strategies. First of all, the business case may need a relatively large space to evolve in order to adapt to changing circumstances and new findings. Especially for radical propositions, uncertainties are high and therefore the priority of various potential technology-product combinations may considerably shift throughout the process. A technology platform may be helpful to provide this flexibility: It enables the team to develop the technological skills needed, while keeping options open towards various applications promises (e.g. Elecsci Corporation). Otherwise, if the company already focuses on a specific combination of one technology and one application, another strategy is needed. Because resources and information are focused the chance of success increases. However, for a proposition with a radical character, many other uncertainties could result in challenges for the business case (for example, Texas Instruments's DLP initiative). Thirdly, building on the above-mentioned technology platform strategy, temporarily a dual strategy can be appropriate, offering services based on the key expertise of the business to support cash-flow, in combination with a clear product paradigm. Apart from providing cash flow, this can provide the team with relevant networks and market information. If such a dual strategy is combined with a clear long term product-market focus, it can result in a strong basis for further growth. A fourth strategy also leans towards services: offering customers innovation on the basis of microtechnology and nanotechnology, while developing suitable platforms into separate product business units or spin-outs (e.g. Zyvex Corporation). A fifth strategy revolves around finding core technological skills and offering them to a customer, such as a foundry that combines production with co-development (e.g. Micronit Microfluidics).

In order to succeed in value creation, a strong vision about the value proposition and the perseverance to pursue it are both critical for a firm to stay on track when pushing its architectural innovation idea towards a regular innovation setting. Further, adequate knowledge about markets, networks and technologies is helpful in order to develop strategies to find a way across the chasm and move the business into new phases of innovation and business generation. International networks such as MANCEF and environments such as universities can support such information needs.

Entrepreneurial behaviour

Architectural innovations come with a low degree of structure and predictability. In such situations, the entrepreneurial quality of the team will be a determining factor in the success of the business initiative. In particular, the ability to accept risks and a flexible attitude are necessary. With regard to risk acceptance and flexibility, teams with young people are expected to perform better because they generally have a more open attitude towards the creation of new networks and the need to change established systems. Further, they are most probably to a lesser degree bothered by vested interests (e.g. Micronit Microfluidics). For large firms, focussing on radical innovation, the key challenges are the risks associated with the introduction of a radically new technology, the limited availability of design standards and the low production volumes and turnover in the early phases of development (e.g. DLP initiative of Texas Instruments). In contrast, small firms run the risk not to pay sufficient attention to opportunities on the business side, being tempted to focus on technology push strategies (Berry and Taggart, 1998; Oakey, 2003). Bringing in experienced leadership is a way to strengthen the team but should be balanced in order to retain ground-breaking potential, vision and entrepreneurial behaviour with regard to the original business initiative (such as the involvement of experienced founders in the Zyvex and Elecsci Corporation initiatives).

The company's environment

The success of a business initiative depends not only on the entrepreneurial factor, but is also strongly related to environmental factors, such as the geographical location and collaborations. A technology-based architectural innovation is generally created and developed by collaborating organisations: small and large companies with or without their own research and development facilities, high-tech start-ups, universities, governmental-funded research organisations and customers (see, for example, the partner management approach of Zyvex). Companies pursuing architectural innovations often link-up with (public) knowledge infrastructures. Here they find bright, young people with a low risk aversion, interesting innovative ideas, an infrastructure for research and development and independence of players with vested interests in established value chains who might strangle entrepreneurial initiatives (for example Elecsci Corporation's link with the Rochester Institute of Technology, and Micronit Microfluidics' interaction with the MESA+ Institute). For actors in such an environment, growth management and capital require special attention, since they do not have the culture and lack the experience to deal with such factors. In general, an open knowledge systems and a collaborative culture can contribute to the nucleation and growth of complementary new business initiatives. Furthermore, the chance to network with players in existing and new value chains can be of great help to create access to markets (for instance, i-STAT partnering with Abbott Laboratories, and Texas Instruments's difficulties in involving actors in the projection business). Finally, for the firms collaborating in such networks, the building of a shared vision and perseverance are essential to successfully develop and commercialise new technologies in the long run.

Implications for knowledge production and policy

To a certain extent, governments operating at supranational, national and regional levels tend to focus on generic innovation-related policies, for example in the form of R&D programmes. However, generic policies are not fully adequate to support architectural innovation, as specific realignments of scientific and technological disciplines, changes in roles of actors and reconfigurations of networks are necessary to succeed in value creation. It is relevant that policy makers are aware of the potential economic implications of innovation in an architectural context. Policy-oriented actors should recognise the innovative output and its importance for a vital industry. Reconfigurations of existing networks can only be effectively made with shared long-term visions and objectives. That is why policy makers have to work in concert with their academic and industrial counterparts to build such a vision and to develop specific policies to realise it. Such policies should be aimed at the creation of nurturing environment that motivates and enables organisations and entrepreneurial individuals to produce, develop and commercialise these so-called architectural innovations. So as to benefit from the oppportunities of converging technologies, knowledge institutes have to create linkages between established scientific and technological disciplines, thereby promoting the necessary combinationof various capabilities. Further, a vision-based policy should provide continuity in the development of research and development infrastructures so as to reduce risk for potential investors in the companies that make use of this infrastructure. Alternative financing models are needed that allow for an increases availability of capital. This requires a more market-driven approach, not only in the companies themselves, but also among the broader set of stakeholders. Finally, governments can foster an entrepreneurial mindsets through education programmes, the facilitation of cross-learning and the provision of facilities.

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