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Financing Innovations in Uncertain Networks –

Filling in Roadmap Gaps in the Semiconductor Industry

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Abstract

Complex technologies are often developed in inter-organisational networks as actors try to reduce development costs and uncertainty about the viability of these innovations. However, as of to date it remains unclear how such innovations are financed collectively under conditions characterised by extreme uncertainty. Hence we explore how financial resources within innovation networks are mobilised and allocated. This question is of particular importance to the development of system technologies that are viable only if *all* critical components are functional on time. We explore this issue by reviewing the development of a radically new system technology for mass manufacturing microchips in the semiconductor industry. In this industry, technological roadmaps allow actors to identify critical components that still need to be developed. These components are the so-called roadmap gaps. However, suppliers can be reluctant to develop the required components at their own expense because of the high uncertainties involved. In such cases, providing financial support to component suppliers is a central task of innovation networks. The empirical analysis shows that semiconductor manufacturers take both an individual and a collective approach to filling roadmap gaps. This study contributes to prior research on innovation networks and financial management not only by identifying and clarifying these two approaches, but also by revealing under which conditions they are used. The findings are particularly relevant to scholars interested in the innovations of complex product systems (CoPS).

Keywords: innovation networks, semiconductor industry, uncertainty, technological roadmaps, finance

1 Introduction

Complex system technologies, such as transportation systems (Neven et al., 1995) and manufacturing technologies (Linden et al., 2000), are often developed in consortia or other types of inter-organisational networks. System technologies are particularly likely to be developed in such innovation networks (Freeman, 1991), as organisations are confronted with high degrees of uncertainty. In line with Knight (1921), we define uncertain situations as those in which not only subjective probability estimates are unavailable to organizational actors to evaluate future outcomes, but the range of options is not even foreseeable. Thus, organisations engaged in the development of complex system technologies often collaborate in networks to not only share the calculable risks and lower the high costs (Davies, 2003), but also to deal with the fundamental uncertainties involved (Appleyard et al., 2008).

In this regard, organizations do not only need to align their own R&D activities, they are also faced with uncertainty at the network- or system-level. The reason is that system technologies are only viable if *all* critical components are serviceable on time. Thus, the failure of a single critical component supplier because of a lack of competence or financial resources could lead to the breakdown of the entire development process of the system technology. As a consequence, none of the firms involved would be able to generate a return on their investments, even if they had developed a functional component on time (Chuma, 2006). Organizations involved in the development of system technologies are therefore confronted with high systemic uncertainty. This problem appears relevant not only for complex products and systems (CoPS; Hobday, 1998) such as in the aircraft, solar energy, or semiconductor manufacturing industries, but also for innovation networks like transnational scientific research centres or public-private partnership networks more generally.[1] Given this

[1] Take, for instance, the large-scale basic research undertaken by the Swiss-based CERN (Conseil Européen pour la Recherche Nucléaire; Boisot et al., 2011). This research centre is in effect a large-scale innovation effort

observation, it is surprising that financing innovations in networks – and here in particular the development of complex technological innovations – confronted by a high degree of systemic uncertainty has received hardly attention in the extant research. In prior network research, the financial dimension has not usually been considered. In the finance literature, the collective nature of financing problems is neglected. Thus, in this study, we ask the following two explorative research questions:

> *How is the development of complex system technologies, usually faced with extreme uncertainties, financed in networks? Moreover, under what conditions do lead firms contribute to financing and when are more collective approaches more likely?*

We answer these research questions by examining the results of a longitudinal explorative study on the quest for a radically new system technology for mass manufacturing microchips called Extreme Ultraviolet Lithography or EUVL. In the semiconductor industry, technological roadmaps allow actors to identify critical components that still need to be developed. These components are the so-called roadmap gaps. The existence of roadmap gaps creates high systemic uncertainty for the entire innovation network, especially if it is unclear which organizations are potentially able and willing to fill these gaps. We show that there are basically two ways to address this systemic uncertainty. First, collective action supported by research consortia or government-funded R&D programmes can be organised (in our case by means of collective roadmap gap financing). Second, a lead firm can emerge and absorb the systemic uncertainty by co-funding the projects of critical suppliers (in our case by means of individual roadmap gap financing).

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consisting of multiple organizations involved. As for a public-private partnership, consider the Diabetes Genetics Initiative of Novartis and three universities that generate insights into diabetes treatment.

Herein we contribute to research by theorizing financing in innovation networks under extreme uncertainty in two ways. First, we identify the mechanisms that the organisations within a network employ to finance roadmap gaps and, thereby, deal with systemic uncertainties. Second, we analyse which mechanisms are used under what conditions. Our findings are summarised in a series of propositions that provide promising avenues for future research on roadmap gap filling in particular and, at least to a limited extent, for financing the development of complex technologies in innovation networks in general.

The remainder of this paper starts with a review of the literature on networks and on financial management relevant to our research question. Subsequently, we describe our research setting, the semiconductor manufacturing industry, which allows us to analyse the financing of system technology development in great detail because of the dominance of inter-organisational networks, the high capital intensity of this industry and the extreme systemic uncertainties involved. In the method section, we introduce our explorative in-depth case study approach. In the empirical part, we first describe the systemic uncertainty that organisations face in the development of EUVL before we outline the two ways to address systemic uncertainties: collective and individual financing of roadmap gaps. Based on our findings, we discuss our results and their generalizability in the light of the literature on CoPS and develop propositions. Finally, we summarise our main contributions, discuss the limitations of our study and point to future research avenues.

2 Financing Innovation in Networks – A Review of the Literature

The management literature is silent not only about financing innovations in networks but also regarding the financial dimension of inter-organisational collaboration more generally, not considering the abundant studies of alliance and network formation on firm valuation (e.g.

Oxley et al., 2009). A related body of studies that is relevant to our research question is the literature on CoPS (Hobday, 1998), as their development takes place mostly in innovation networks and is confronted by financing problems. Examples of CoPS include aircraft carriers and aero-engines. Similar to the semiconductor manufacturing equipment industry, that of aero-engines is characterized by various fundamentally different technologies, an extremely high amount of components, a highly specialised supplier base, an abundance of networks, high interrelatedness of sub-systems/components, soaring R&D costs, and significant uncertainty regarding the success of development programmes. Key suppliers often become so-called risk and revenue partners (bilateral agreements) and buy stakes in development programmes of aircraft engines (Acha et al., 2007; Brusoni and Prencipe, 2011; Figueiredo et al., 2008; Luz and Salles-Filho, 2011). However, the character of these financial deals is different from that in the semiconductor manufacturing industry. In the aero-engine industry, key suppliers buy a stake in development programmes and, thereby, reduce the financial risk for the engine manufacturers, while in the semiconductor manufacturing industry system integrators provide critical suppliers with financial resources to reduce their development risk.

The finance literature is hardly concerned with financing beyond the boundaries of the single firm (Brealey et al., 2006), with the exception of project finance. According to Esty and Megginson (2003, p. 39), "project finance is defined by the creation of a legally independent project company financed with non-recourse debt for the purpose of investing in an industrial asset". Project finance operates with a high debt-to-total equity of 70% on average (Esty, 2004). Because of the project companies' high levels of debts and the non-recourse character of the debts, lenders are only willing to provide loans if the company's cash flows are quite predictable. However, high-risk development projects do not have predictable cash flows (Yescombe, 2007). Moreover, the few empirical studies on project finance that exist (Dailami and Hauswald, 2007; Esty and Megginson, 2003) do not study the interactions between the actors involved. More recently, Boone and Ivanov (2012) have at least investigated the possible spill-over effects of the bankruptcy of an alliance or network partner on the valuation and operating performance of the others. While these insights are not directly relevant in light of our specific interest, Leitner (2005) answers our research question to some degree. The researcher modelled a scenario in which liquid banks might bail out illiquid banks with which they are financially interwoven to prevent the breakdown of the entire financial network. However, the author focuses on developing a model for the optimal network size for a possible bailout instead of determining the type of coordinative practices actors actually use to address such network problems. The case we are looking at also differs in another important respect: instead of being illiquid, the firms only lack the ability or willingness to finance an innovation on their own.

Furthermore, venture capital (VC) firms are known for financing the high-risk development of small entrepreneurial firms (Gompers, 1995) and taking on an organizing role in networks (Lindsey, 2008). Thus, VC firms could help directly and indirectly to fill the roadmap gaps. However, the characteristics of the gaps in the chip industry's roadmap are not conducive to the type of start-ups that VCs prefer, as VCs typically have a limited time horizon and usually intend to exit their investments after no more than 5 years (Chesbrough, 2000; Harding, 2002). With regard to the system technology under scrutiny, it is difficult to predict when VCs will be able to exit their investments because the conventional technology, optical lithography, has been extended constantly (Henderson, 1995; Linden et al., 2000; Appleyard et al., 2008; Sydow et al., 2012). Additionally, the semiconductor industry has been consolidating in recent years (The Economist, 2009), and the pool of potential customers for any new manufacturing technology has shrunk constantly. Hence, even if a new technology were successfully introduced into mass manufacturing, the markets for the components and tools might be limited.

Corporate venture capital (CVC) is worth mentioning, as it comprises risky investments by large companies in start-up firms with a longer term perspective (Chesbrough, 2000). Among the several types of CVC investments, ‘driving investments’ are most relevant. They are characterised by a strategic rationale and strong interrelations between the operations of the investing company and the start-up. An example of this type of investment is large corporations’ investments in their supply chains (Chesbrough, 2003). Therefore, it is possible that large companies, which depend on the realization of such a system technology, use this financing instrument to fill roadmap gaps, as we will show later.

From the field of economics, the literature on the collective action problem (Olson, 1971) and game theory (von Neumann and Morgenstern, 1944) are theoretically relevant. Because all members of the innovation network would benefit from the filling of the roadmap gaps, a single company might not have an incentive to finance it single-handedly. However, such problems of system technology financing have not yet been addressed by the collective action literature. Game theory is relevant to our study because it addresses groups of actors and their strategic interactions. However, it does not consider the social embeddedness (Granovetter, 1985) of economic interactions in general and in innovation networks in particular. The game theory contribution that comes closest to our research question is that of Kim and Netessine (2011), who focus on highly complex and innovative product companies and on the uncertainties of demand and production costs. The uncertainty of a failure in the system technology’s development process due to the lack of a critical component is not addressed.

In brief, the management literature on innovation networks does not consider the mobilisation and distribution of financial resources within networks with the aim of encouraging critical component suppliers to initiate and maintain their development programmes. Only the acquisition of stakes in development programmes of engine manufacturers by key suppliers to reduce the manufacturers’ risk is considered. From the finance literature, we only identified

CVC investing as a financing instrument that could be used by members of an innovation network to fill roadmap gaps. Thus, the research question addressed in this paper has yet to be explored.

3 Research Context: the Semiconductor Industry and the Development of a Radically New Manufacturing Technology

Although the semiconductor industry is special in several respects, financing in innovation networks is relevant to other settings as well; for instance, to the pharmaceutical industry (e.g. the Diabetes Genetics Initiative) or basic research in physics by CERN. Moreover, technology roadmaps are used in many industries such as the oil, chemical, alumina and forest products industries (e.g. Barker and Smith, 1995). According to Phaal (2011), more than 2,000 roadmap documents (e.g., targeting industries, organizations or networks) are available on the Internet, reflecting the omnipresence and managerial relevance of this phenomenon. However, the use of an industry-wide road mapping process originated in the research context that we focus on: the semiconductor industry.

A long-established research consortium such as Semiconductor Manufacturing Technology (SEMATECH) that has a history of funding supplier development costs is uncommon in most other industries (Browning and Shetler, 2000). Furthermore, in the case of EUVL, the radically new system technology analysed in this paper, the challenges are extreme because for many components, there are only one or two suppliers worldwide that can develop these components. More often than not the development is carried out at the edge of established knowledge in physics. Despite these peculiarities, the development of system technologies in the semiconductor industry has many similarities to the development processes of other CoPS industries. Examples of these include the multi-component and multi-technology character, the dominance of networks, the specialised supplier base, and the high development costs. In addition, we submit that the large-scale investments required to face future technological challenges exceeding a single firm's capabilities are not unique to the semiconductor industry. For instance, as one interviewee reported, the US government seems to be establishing pre-competitive research and development consortia in the solar and automotive industries that use SEMATECH as a role model; not least with regard to the way technological challenges are addressed by financing within these networks.

Furthermore, there are two trends discernible in industries characterised by systems integration that increase the probability that the leading members of innovation networks will have to establish mechanisms to financially support critical suppliers. First, the knowledge base is becoming increasingly complex and specialised (Brusoni et al., 2001; Bullinger et al., 2004; Dhanaraj and Parkhe, 2006), putting extra demands on processes of knowledge integration (Berggren et al., 2011). Hence, in such industries, the lead firms or "network orchestrators" (Dhanaraj and Parkhe, 2006) will be confronted increasingly with the need to have to rely on a limited number of suppliers for a critical component. Second, in many industries there is a trend towards increasing developmental costs (Lin and Chen, 2006; Millson and Wilemon, 2008/2009; Sammarra and Biggiero, 2008). As a consequence, critical component suppliers may not be able or willing to finance the development process on their own, and mechanisms may need to be established to financially support critical suppliers. Because the semiconductor industry is characterised by distributed science-based knowledge and is dominated by inter-organisational networks, high capital intensity and extreme systemic uncertainties (Appleyard, 2008; Tsai et al., 2009; Sydow et al., 2012), this setting provides a unique opportunity to analyse the financing of system technology development in innovation networks. In other words, we consider this industry an ideal testing bed for future challenges in CoPS industries.

Semiconductor manufacturing technology is structured as follows: the light of a source travels through an optical system and exposes the structure of a mask on the resist, which is the photosensitive lacquer on the wafer. By doing so, the light creates a pattern. The production of all three main components (i.e., the optical system, the mask and the resist) requires cutting-edge science. Thus, the successful development of this manufacturing technology is highly demanding and depends not only on overcoming knowledge deficiencies but also on coordinating the development of a complex system that cuts across three distinct supply chains: the lithography system, the mask, and the resist. The supply chain of the lithography system consists of the lithography tool, the light source and the optical system. The mask and the resist constitute the two other supply chains.

The large semiconductor manufacturers like Intel and the suppliers of lithography systems like ASML coordinate these supply chains and their development activities (see Figure 1).

Insert Figure 1

There are only three suppliers of lithography systems worldwide: apart from ASML (from the Netherlands), these are the Japanese companies Nikon and Canon. Components and materials are developed by a multitude of suppliers and sub-suppliers, universities and research institutes around the world. Additionally, the development process is assisted by government agencies (Chuma, 2006).

R&D consortia (e.g. SEMATECH) hence coordinate the development activities on a global scale, and their members need to constantly realign their interests as consensus in pursuing network objectives is not the norm (Das and Teng, 1996; Huxham and Vangen, 2005); not least when facing extreme uncertainties. SEMATECH is central to guiding the so-called pre-competitive technological development of the semiconductor field (Grindley et al., 1994; Sydow et al., 2012) and prepares the ground for tackling the problem of financing roadmap gaps.

4 Research Methods: Rationale, Data Collection and Analysis

This study stems from a major research project (2003-2010) focusing upon the development of technological options in the semiconductor industry by means of inter-organizational collaborations. While we were aware of the relevance of inter-organizational collaborations, not least because of earlier studies (e.g. Browning and Shetler, 2000; Linden et al., 2000), we did not understand the conditions and ways of financing in innovation networks. In face of the extreme scarcity of research at the intersection of financing and innovation networks, we focus on ‘how’ and ‘why’ questions, using a theory-building approach (Yin, 2009). Moreover, addressing historical processes involving multi-actor constellations (here: organizations and networks financing and pursuing differing technological options) represents a complex embedded setting where inductive techniques offer the possibility to disentangle the differing interests pursued and where deductive, theory-testing approaches would appear to be premature (Eisenhardt and Graebner, 2007; Langley, 1999).

For the *data collection*, we utilised three main sources for triangulation purposes to heighten the construct validity (Yin, 2009). First, we used archival data consisting of press releases, newspapers trade press periodicals (e.g. Intel Technology Journal, SEMATECH archives or Solid State Technology) and organizational data (e.g. SEMATECH archives, ITRS roadmap documents). Archival data as a form of secondary data are deemed to be useful, as they allow us to reconstruct a general picture of the organisational field.

Second, by now we have conducted 111 interviews in the US, the EU, and Japan with senior executives and technology experts from semiconductor manufacturers and their supplier base as well as from different consortia (see Table 1). We conducted 96 interviews during the course of the project (2003-2010) and 15 follow-up interviews until October 2012. The interviewed experts included a panel of five informants with different organisational and professional backgrounds and deep insights into the technology development process. Four rounds of panel interviews were conducted from 2007 to 2010 to allow for a real-time investigation of the technological development process. Additionally, venture capitalists and government agencies were interviewed.

The semi-structured interviews were 60-90 minutes in length.[2] They focused on various topics, such as the coordination of the development process for system technologies designed to mass manufacture semiconductors, the collaborations among competitors and along the supply chain, and the stage of development of EUVL. Topics more specific to the research question investigated in this study included the financing requirements regarding EUVL, the variations in these requirements for different types of actors, the uncertainties related to EUVL, the motivation to pursue R&D efforts in this direction, and the identities of the key actors who provide financial assistance to critical members of the EUVL innovation network.

[2] Panel interviews were an exception in this regard and lasted only approximately 30 minutes on average.

Table 1: Field interviews (* panel member)

Type of Organisation	*Region*	*Number of Interviews*
Supplier	EU	34*
	US	4
	JP	4
Consortium	EU	4
	US	23**
	JP	4
Chip Manufacturer	EU	9*
	US	7*
	JP	1
Agencies / Ministries	EU	4
	JP	1
Research Organisation	EU	4
	US	5
	JP	1
Venture Capital	EU	4
	US	1
Consultants	EU	1
Sum		*111*

Third, direct observation at seven industry conferences (in 2001, 2005, 2009-2011) facilitated a better understanding of the most pressing issues regarding EUVL. At these occasions we were not only able to acquire first-hand insights about how technological developments are staged and (re)interpreted; we also strengthened the validity of our claims by formal and informal conversations and data gathering (e.g. roster listings, leaflets or conference presentations). At these venues we also conducted an additional 15 impromptu interviews (varying in length between 5 and 60 minutes) and as suggested by Yin (2009) we took extensive notes within 24 hours after each venue had finished.

Data analysis occurred in roughly three stages. First, based on our ‘raw data’ of approximately 1,200 pages of archival data and interview transcripts, we examined the activities of the different organizations and inter-organizational collaborations as a first step.

The second stage consisted of writing up condensed descriptions of how financing occurs by different types of organizations (e.g. Intel) and inter-organizational collaborations (i.e. networks like SEMATECH or projects in the case of the EUV LLC). The resulting detailed descriptions were discussed by the research team and used to discuss the way in which financing occurs in the semiconductor industry. In stage three, the empirical data were condensed by combining all the information for a joint analysis. Figure 2 shows an overview of the emergent data structure that surfaced with coding in-vivo to generate first-order categories (i.e. using terms generated from our interviews and observations). To qualify for being integrated into the analysis as a code, codes had to occur frequently and be perceived as relevant by actors from the field (Glaser and Strauss, 1967). At first, codes were represented by text units that were placed in multiple categories to allow for a rich interpretation of data. Conflicting interpretations among the interviewees were cross-checked with archival data and where necessary we re-entered the field, conducting follow-up interviews to heighten construct validity (Yin, 2009). The initial coding resulted in first-order categories that were provided as in-vivo codes by informants. Subsequently, we constructed mutually exclusive second-order themes and grouped them hierarchically, which led to the collapse of the first-order categories into second-order and later on third-order themes that represented more abstract and researcher-induced interpretations. This approach enabled us to develop underlying generalizable constructs and relationships concerning financing in innovation networks under systemic uncertainty; first and foremost, the concepts of roadmapping and roadmap gap filling. Table 2 provides illustrative evidence and data sources for the third-order themes of collective and individual roadmap gap filling.

Insert Figure 2

Table 2: Illustrative evidence and data sources for collective and individual roadmap gap filling

Form of roadmap gap filling	Data source	Illustrative evidence
Collective roadmap gap filling		
	Archival data	”Sematech’s efforts became the basis for the development of aggregate technology roadmaps that could identify technical opportunities and gaps that had not previously been brought to light” (Hamburg Institute for Economic Research et al., 1996: 147-148)
	Interview data	“[SEMATECH’s purpose is to] drive the industry roadmap, you know the tactical roadmap for semiconductors where it tells you how you can come from one node to the next node [and to] coordinate industry infrastructure” (I-79)
	Observational data	“Both in a presentation and in informal conversations during coffee breaks where I [one of the authors] joined conversations with B.R. [Director of Lithography of SEMATECH], B.R. announced that the results of the SEMATECH Workshop on EUVL Mask Infrastructure resulted in a clear mandate for SEMATECH to form a tool consortium to fund the development of EUVL mask metrology equipment. However, it remains 'Uncertain what funding model would be successful' as he stated on one of his slides presented during the conference” (excerpt from notes taken during the 2009 International Symposium on Extreme Ultraviolet Lithography, Prague / Czech Republic, October 18-23, 2009)
Individual roadmap gap filling		
	Archival data	“Intel continues not only to evaluate the suppliers it has engaged, but also to stay aware of the other potential solutions […] We decided to […] engage with suppliers to develop tools required to make a final EUV mask so that we could demonstrate to the industry it could be done while developing the industry infrastructure” (Golda and Philippi, 2007: pp. 101-102)
	Interview data	“We might be ahead of the needs of our manufacturing group. We look at what we call gap filling activity. So if there is a known technology gap or a manufacturing capability gap, we can use money off of our balance sheet in the form of equity investment to try to create solutions for gaps on a roadmap and then again perhaps the last one is more of an ecosystem approach where we are working with key companies in the silicon supply chain“ (I-97)
	Observational data	“I approached an Intel Capital representative during the lunch break […] and he argued that Intel always tries to have alternative suppliers at hand in order to prevent being dependent upon a single supplier, which is why Intel Capital pursues both strategic (i.e. in line with Intel Corporation) and venture capital (i.e. financially attractive) objectives” (excerpt from notes taken during the Litho Forum 2010 in New York City, May 10-12, 2010)

5 Financing the Roadmap Gaps of EUVL: Collective and Individual Approaches to Addressing Uncertainty

In the following, we present our empirical findings, which focus on the extreme uncertainties related to the development of EUVL (5.1). These findings are followed by an examination of a collective approach (5.2) and an individual approach (5.3) to financing roadmap gaps. Both approaches turn out to be capable of solving the problem of financing the roadmap gaps that emerge in innovation networks. The timeline of SEMATECH's (collective approach) and semiconductor manufacturers' (individual approach) EUVL engagement is provided below (Table 3). This timeline contains selected key engagements.

Table 3: Timeline of SEMATECH's and semiconductor manufacturers' selected key engagements regarding EUVL

SEMATECH

- SEMATECH and University at Albany-SUNY close deal on EUV Lithography program (2003)
- SEMATECH and Exitech agree to develop the world's first aerial image monitor tool for the inspection of EUV reticles (2003)
- SEMATECH and SCHOTT Lithotec agree on development of EUVL mask blanks (2003)
- SEMATECH announces industry-wide EUVL mask blank exchange program (2004)
- SEMATECH reaches milestone in defect cleaning for EUVL mask blanks (2007)
- SEMATECH and TOK agree on joint development of next generation resists for EUVL (2009)
- SEMATECH and ASAHI Glass agree on joint development to commercialize defect-free EUVL mask blanks (2009)
- SEMATECH kicks off consortium to develop crucial EUVL metrology tools (2010)
- SEMATECH and Carl Zeiss to develop EUVL metrology tools (2010)
- SEMATECH and Applied Seals partner to enable defect free EUVL masks for high-volume manufacturing (2011)

Semiconductor manufacturers

- Development agreement between Intel and Nikon (lithography systems; 2002)
- Intel Capital invests in Nawotec (mask equipment; 2002)
- Development agreement between Intel and Cymer (source; 2004)
- Intel Capital invests in Media Lario (mask equipment; 2004)
- Development agreement between Intel and Corning (mask material; 2005)
- Intel Capital invests in XTREME (source; 2006)
- Intel Capital invests in Energetiq (source; 2006; 2nd round of financing in 2008, 3rd round in 2009)
- Intel invests in ASML (lithography systems; July 2012)
- TSMC invests in ASML (lithography systems; August 2012)
- Samsung invests in ASML (lithography systems; August 2012)

5.1 Systemic Uncertainty in the Development of EUVL for the Suppliers of the Semiconductor Industry

By the mid-1990s, the actors in this industry realised that the basic technology for manufacturing semiconductors, optical lithography, was facing its technological and commercial limits. It became clear that the next generation technology would break away from the current technological path to meet the constantly increasing demands of the customers. Five post-optical lithography options were competing for supremacy. Electron Projection Lithography (EPL) was considered the most promising post-optical lithography option (I-1/Agency) until 2000. Extreme Ultraviolet Lithography (EUVL) emerged in 2001 as the most promising post-optical option because of its proof of principle (see 5.2). In addition, industry experts became increasingly sceptical because EPL would have required even more drastic changes in the supply chain. Unlike optical lithography and EUVL, EPL relies on particles instead of photons, which would have required huge changes in the existing supply chain (I-3/Supplier). However, it is still unclear whether EUVL will prevail in the end. The ITRS also lists five competing technologies to manufacture 16nm chips in 2016.[3] EUVL was massively supported by the market leader Intel, which had already backed EUVL when virtually no other actors saw it as worthwhile (Linden et al., 2000). Intel had recognized, at an early stage, the advantages of a photon-based post-optical lithography (I-33/Chip Manufacturer). This early and deep commitment provided Intel with special knowledge about this lithography option. This knowledge might have rendered Intel more willing to utilise EUVL over the other options and to fund its development.

The companies and networks involved in developing and financing the critical components for this system technology face high uncertainty, as EUVL represents a radically new system technology where several completely new challenges emerge, as for almost *all components*, meeting the technical and economic specifications in time is difficult. The failure to develop a

[3] Roadmap gaps do not only exist for EUVL but also for other lithography options. For the extension of optical lithography in the form of 193 immersion, multiple patterning further to the 16-nm node, the industry needs to develop a new liquid with a higher refraction index, which is a new challenge (I-40/Supplier). Finally, lithography is only one area of the industry roadmap. Other areas, such as design, testing and materials, also face critical gaps in their respective roadmaps. For 2019, the key challenge for the manufacturing of 11nm chips is most likely to be not the lithography per se but the development of perfectly smooth materials (I-74/Consortium).

single critical component can jeopardise the entire development process of the system technology. The systemic uncertainty in the case of EUVL is extreme because several crucial components depend on a large number of sub-components and a whole network of their respective suppliers. Additionally, only one or two suppliers worldwide can develop some critical components. As a result, several suppliers have become deeply sceptical, as the possibility of a breakdown in the development process of the system technology is considerable given the exceptional challenges of EUVL. As many critical suppliers lack substantial financial resources, the financial consequences of this high uncertainty are of particular concern to them. A failure of the entire EUVL development process could lead to the bankruptcy of suppliers that have invested heavily in the development of this technology.

Furthermore, the development of EUVL has taken far longer than expected, rendering the situation even more incalculable. Although SEMATECH estimated in 1997 that the development process would take 8-10 years (Linden et al., 2000), the introduction of EUVL into mass manufacturing has been considerably delayed. At the moment, EUVL is expected to be introduced in 2013, but the introduction could either fail or be postponed again (I-109/Chip Manufacturer). Even if EUVL is successfully developed, if the period between the investment in the development of a specific component and the commercialisation of EUVL is too long, the suppliers might go bankrupt. This is a further reason why the suppliers are quite reluctant to invest. By contrast, the semiconductor manufacturers, such as Intel, are in dire need of this new technology. Hence, they have high incentives to finance the filling of critical roadmap gaps. In the following, we present two distinct approaches to filling the gaps in the EUVL roadmap: a collective and an individual practice.

5.2 The Collective Practice of Roadmap Gap Filling: Multi-Actor Partnerships

Government agencies and research consortia have been involved in the collective practice of ‘roadmap gap filling’ for years. Government-funded programmes in the US, Europe and Japan have been crucial to the development of EUVL and the financing of suppliers, systems integrators and component suppliers. Furthermore, three consortia – the EUV LLC, SEMATECH and the EUVA – have been of central importance. Because SEMATECH is the only global consortium in this industry and the most important one with regard to the financing of roadmap gaps, most emphasis will be put on this organisation.

The development of EUVL started in the US. In 1991, three national laboratories (Lawrence Livermore National Laboratory, Sandia National Laboratory, and Lawrence Berkeley Laboratory) and eight companies (AT&T, Ultratech Stepper, Intel, Jamar Technology, AMD, Tropel, Micron, and KLA Instruments) signed a Cooperative Research and Development Agreement to conduct a feasibility study. This study was funded by the Department of Energy and the participating companies. In 1996, the Department suspended the funding (ElectroIQ, 1997). Intel became active and established the privately funded EUV LLC consortium in 1997 (see also Gwyn and Wurm, 2009). The founding members were Intel, AMD, Motorola and three national laboratories. The budget amounted to $250 million, and Intel was the majority shareholder. ASML joined the consortium in 1999 (Electronic News, 1999), whereas Micron and Infineon joined in 2000 (ElectroIQ, 2001). IBM’s decision to join in 2001 was particularly important, as it was not only a large player but had also previously supported the competing EPL. In 2001, the consortium successfully developed a prototype. Because of its proof of concept and the support of several large chip manufacturers, EUVL gained legitimacy and its roadmap emerged as the dominant one for post-optical lithographies. This made it a technological option worthy of attention from the perspective of suppliers (I-1/Supplier).

As a consequence, SEMATECH established a large EUVL programme to finance the filling of roadmap gaps.

"The EUV LLC was the start. It demonstrated the feasibility of EUVL by building this ETS [Engineering Test Stand] tool. Then it [the EUVL development] went to SEMATECH" (I-23/Chip Manufacturer).

After the breakthrough of the EUV LLC, EUVL became much more central to the publicly funded R&D programs in Japan and Europe. In the EU, five projects focused on the development of EUVL under the umbrella of the MEDEA+ programme: EXTATIC, EXTUMASK, EUV Sources (all 2001-2004), ExCITe (2003-2005) and EAGLE (2006-2008). Additional EU-funded projects were MORE MOORE (2003-2006) and EXEPT (2009-2011). To the suppliers short of financial resources, this type of government support was often crucial:

"EUVL is a high risk business. It requires huge amounts of money. An unreasonable amount of money, which we have to invest into this technology. And its introduction into high volume manufacturing and the generation of a return on investment is many years away [...] The introduction of such technologies always takes much longer than usually expected and in this respect government funding is vitally important. Particularly in times of downturn when it becomes more difficult to fund the development internally" (I-3/Supplier).

This testimony shows that the long development process is a problem for the suppliers, in particular component suppliers, and that government funding can mitigate the problems caused by its length.

In Japan, a consortium was established in 2002 to fill the EUVL roadmap gaps independently: the Extreme Ultraviolet Lithography System Development Association (EUVA). The consortium included semiconductor makers, suppliers of lithography systems and source suppliers from Japan and was financially supported by the New Energy and Industrial

Technology Development Organisation until 2010. The main focus was on the development of a source. The driving forces behind the establishment of the EUVA were Canon and Nikon, which – as leading systems suppliers – asked the Japanese government for funding (I-55/Consortium). In 2011, a new consortium consisting of eleven Japanese companies was established: the EUVL Infrastructure Development Centre (EIDEC). It is supported by Japanese government agencies and has forged links with non-Japanese chip manufacturers (EIDEC, 2011). The consortium has become active in financing the EUVL roadmap gaps and is currently funding the development of a metrology tool (ElectroIQ, 2011).

The most important actor by far regarding the collective financing of roadmap gaps, however, is SEMATECH, as it is the only consortium that financially supports the EUVL suppliers and the filling of the roadmap gaps on a *global* scale. SEMATECH also has the most experience in filling the roadmap gaps for EUVL. SEMATECH's overall budget for the consortium is a well-kept secret but was estimated to be between $100 million (I-88/Consortium) and $140 million (I-31/Consortium). SEMATECH's financial resources originate from its members' fees, which are linked to their turnover and royalties from the companies that have brought SEMATECH-funded products to market. The consortium has five divisions. The lithography division is the most important in terms of funding. The consortium regards itself as a filler of roadmap gaps pertaining to future lithography technology options such as EUVL and high-index immersion lithography (I-67/Consortium). In 2003, following the proof of concept by the EUV LLC, SEMATECH became engaged in the EUVL development process. SEMATECH and the University at Albany-SUNY closed a deal on a five-year EUVL program.

To monitor the progress of EUVL and to identify gaps in its roadmap, SEMATECH collaborates with the International Ultraviolet Extreme Lithography Initiative (IEUVI), which is a loose confederation of consortia that includes Japanese consortia. Japan is crucial for several components of EUVL, but because of language barriers, geographical distance and cultural reasons, the Japanese tend to conduct R&D in Japan-centric groups (Ham et al., 1998). The dominating actor within the IEUVI is Intel, although it is formally led by SEMATECH:

"Intel has been a leading proponent of EUVL [...] I think an important example is the establishment of the so-called IEUVI, and that was spearheaded by Paolo Gargini from Intel and I think he basically caused this to be set up and caused SEMATECH to kind of lead this, but it was really very much an Intel-centred, not centred, but initiated activity. [...]. His [Paolo Gargini's] networks are very deep and very substantial" (I-32/Consortium).

To fill the EUVL roadmap gaps, SEMATECH works mainly in joint development projects with suppliers, and the purchase price of the tool/component to be developed by the supplier is often pre-specified. In 2003, the consortium closed financial deals with Exitech to develop an aerial imaging (metrology) tool and with SCHOTT Lithotec to develop mask blanks. In the following year, SEMATECH announced a EUVL mask blank program which entailed collaborative arrangements with several suppliers to develop EUVL mask blanks. In 2009, SEMATECH and TOK agreed on the joint development of a EUVL resist. Furthermore, related to the mask blank program, the consortium entered agreements with Asahi Glass in 2009 to accelerate the mask blank commercialization and with Applied Seals in 2011 to enable defect-free masks for high-volume manufacturing.

Usually, a single supplier is promoted by SEMATECH, but sometimes two competitors are supported to fill a roadmap gap jointly (I-31/Consortium). If there is extremely high uncertainty regarding which technological concept, if any, is viable, SEMATECH may even support two competing projects to fill one gap. This option applies not only to the area of lithography but also to other areas of the SEMATECH industry roadmap, such as front-end process technologies (I-109/Chip Manufacturer). However, this financing approach is only pursued if the related market can accommodate two suppliers (I-86/Consortium).

SEMATECH's rationale is not only to fill particularly critical gaps but also to reduce the systemic uncertainty surrounding the development of this technology and to encourage other suppliers to initiate and maintain their EUVL development efforts:

"SEMATECH puts money into funding key challenges in the technology. The idea is to lower the risk by addressing the challenges of the technology and, thereby, to convince companies to invest their own dollars" (I-32/Consortium).

Furthermore, SEMATECH promotes critical areas of EUVL in which the financial incentives for companies to invest are low:

"One of the major areas that SEMATECH tries to focus on is mask technology. The issue there is, it's a very small subset of the industry, mask making, and quite frankly it's not very profitable, because of the amount of R&D you have to spend for the next technology generation and then what happens is that you only sell four or five tools. Because there are not many mask shops in the world and so it's a very difficult industry. Yet it's vital for the industry overall. So what we do is to subsidize that piece of work" (*I-79/Chip Manufacturer).*

This evaluation was shared by a venture capitalist:

"A very important role of SEMATECH will be stimulating R&D and solution creation, in particular for parts of the manufacturing market, where the market dynamics are challenged. High development costs, a long time to development and the perceived end market may not be that large" (I-84/Venture Capital).

A manager of a mask supplier and a former SEMATECH mask programme manager also confirmed this view. According to him, neither the mask supplier nor Exitech, the first firm that tried to develop an aerial imaging tool, would have initiated EUVL development activities without the support of collective gap financing (I-46/Supplier). This testimony shows that SEMATECH often becomes active when critical tools or components are in danger of not being developed because the respective market is too small to generate an acceptable profit.

Despite the crucial role of SEMATECH in promoting EUVL, it needs to be emphasized that this policy is challenging for two reasons. First, SEMATECH is a multi-technology research consortium whose priorities are heavily debated amongst its members (e.g., Samsung supports EUVL, whereas companies such as Hewlett-Packard promote alternative technologies because of different technological needs). Second, all of the members have equal voting rights with regard to the design of the consortium's R&D programme. Hence, it comes as no surprise that the decision processes within the consortium are characterised by conflicting interests, power struggles and political compromises.

SEMATECH's board has the challenging task of addressing these conflicts. Compensation deals are particularly important in this respect. This fact suggests that the members that do not have an interest in EUVL are compensated for their support by the other members promoting EUVL. That is, the latter members support projects favoured by the former members:

"Lithography meetings, this was where we decided basically where the money would be spent, on what project, a kind of negotiation of how much money would get into, be put into which programs. You know, some companies have little or no interest in EUVL. However, there was some very strong member support for EUVL from very crucial members. And people recognized that they could not just veto everything that they did not like. We kind of balance the funding according to the level of support from the different members. There were some projects that member X wanted to see that member Y did not necessarily support and then X supported a project that Y wanted" (I-67/Consortium).

After Exitech's failure to develop a functional aerial imaging tool, SEMATECH tried to convince Zeiss to develop this tool. However, Zeiss was reluctant to initiate the project without a sufficient number of customer orders. To fund the development of this tool and to tackle other gaps in the area of EUVL metrology, SEMATECH established a global consortium, the EUVL Mask Infrastructure (EMI) partnership, which includes six firms in the semiconductor industry. A press release emphasised that the rationale behind the formation of this new organisation was *"the filling of an industry need considered too costly for individual companies to develop independently. [...] EUVL mask defectiveness is the single greatest challenge to EUVL readiness, but finding the defects requires metrology tools that do not yet exist" (SEMATECH, Newsreport 18 Feb 2010).*

An interviewee confirmed this view:

"The number of tools that will be purchased is small and the risk of investing too quickly and not timing the introduction properly is such that the individual suppliers are very reluctant to invest their money without commitment from the industry" (I-86/Consortium).

In July 2010, this newly established consortium became active. SEMATECH and Zeiss announced their agreement to develop the urgently needed metrology tool (SEMATECH, 2010). This demonstrates again the central role of SEMATECH in financially supporting EUVL suppliers.

5.3 The Individual Practice of Roadmap Gap Filling

In addition to this collective practice, in some instances Intel, as market leader of the semiconductor industry, chose to financially support the suppliers on its own. Aside from Intel, two other powerful actors in the industry – Samsung and Taiwan Semiconductor Manufacturing Company (TSMC) – became active in 2012 in individually financing the filling of the EUVL roadmap gaps (henceforth called individual gap financing). Two mechanisms are employed to support EUVL suppliers financially: (1) joint development projects between semiconductor manufacturers and EUVL suppliers, which can be combined with equity investments. This usually implies that the supplier receives funding to perform specific development tasks; (2) corporate venture capital investments in EUVL suppliers (so far only employed by Intel's CVC entity Intel Capital). As these kinds of individual gap financing lower the systemic risk of a breakdown in the EUVL development process and create incentives for other suppliers to participate in this R&D venture, they have a strong network character, even though the relations underlying these agreements are often dyadic.

According to a document published by leading Intel managers (Golda and Philippi, 2007), the funding mechanism they employ to finance a gap depends on the financial return and on the competitive advantage to be gained. The latter can be realized in the form of earlier access to the product, better commercial terms on the product, or the right to get royalties on the marketed product. If both the financial return and the competitive advantage to be gained are low, Intel tries first to finance the gap via a consortium. If the financial return is low but the expected competitive advantage is high, Intel prefers joint development projects. If the expected financial return is high, Intel opts for a financial investment in the company and if the competitive advantage to be gained is also high, they complement this with a joint development agreement (Figure 3). The importance of high financial returns as a precondition to financial investments was also emphasized by an Intel Capital manager. Moreover, Intel Capital only invests if independent VCs are willing to co-invest, as these co-investments are deemed a market test. The participation of other VCs allows Intel Capital to access their networks and complementary expertise (I-54/Venture Capital).

Insert Figure 3

Intel has individually financed gaps via joint development agreements and CVC investments in the areas of lithography systems, light sources, mask materials, and mask equipment. This reduced the systemic uncertainty of the EUVL development process. Intel's engagement signalled to the industry that it was committed to EUVL (I-43/Chip Manufacturer), which also encouraged suppliers to initiate EUVL development activities:

"Intel has created an entire eco-system that they coordinate on a global scale. They came up with this whole EUVL story. I guess they have invested only $ 100-150 million out of their own pocket (date of interview: 2006),

but the total volume invested in EUVL to date is in the region of $ 1.6 billion. But they created the motivation and they were the locomotive" (I-45/Supplier).

In 2002, Intel engaged for the first time in individual gap financing regarding EUVL. They purchased convertible bonds from Nikon to the sum of £ 80 million. In exchange, Nikon initiated R&D activities for EUVL, even though it had initially supported EPL (I-1/Supplier). Until 2001, only ASML was developing EUVL. Intel's rationale behind the investment was to prevent a situation in which the company would not be able to use EUVL because of ASML's failure to develop the technology. Additionally, Intel sought to stop ASML from capitalising on a monopoly. The interviewees confirmed that establishing a second supplier is also important to semiconductor manufacturers in other areas (I-45/Supplier; I-46/Supplier). Furthermore, Intel invested in three source suppliers, a particularly critical gap: Intel reached a development agreement about $20 million with Cymer (2004), and invested in XTREME and Energetiq via Intel Capital (both 2006). All three suppliers pursued different technological approaches and it was unclear which approach would work. Intel did not anticipate that all three suppliers would succeed, but wanted to ensure that at least one supplier would develop a functional source. According to Intel, all three engagements would provide high financial returns and/or a significant strategic advantage if the suppliers succeeded (Golda and Philippi, 2007). XTREME was acquired by the lighting manufacturer Ushio two years later. Energetiq secured a second round of investment in 2008 and a third round in 2009, in which Intel Capital and independent VCs such as Shea Ventures participated. Moreover, Intel Capital invested[4] in the mask equipment suppliers Nawotec in 2002, which was acquired by Zeiss three years later, and Media Lario (2004). Both start-ups do not rely solely on the success of EUVL because their products and technologies can also

[4] Intel also supported another mask equipment supplier, which did not succeed and went out of business, but the employed funding method is unclear and the name of this supplier is unknown. We need to emphasize that the names of the supported suppliers are not disclosed in the report by Golda and Philippi (2007). However, archival analysis and interviews helped us to identify most suppliers that are mentioned in this report.

be commercialised in other markets (Nawotec can already apply its technology to optical lithography (I-77/Venture Capital) and Media Lario to medical products (I-41/Supplier)). Furthermore, Intel reached development agreements with two mask material suppliers: the name of one supplier, and the time of investment, was not disclosed; the other supplier funded was Corning (2006).

Finally, Intel and also TSMC and Samsung invested in ASML, the European supplier of lithography systems. ASML had announced a co-investor programme in July 2012. It offered up to 25% of the company to its three most important customers – Intel, TSMC, and Samsung – to fund and accelerate its R&D in exchange for € 4.19 billion in share sales and € 1.38 billion in R&D investment. As evidenced in Table 4, ASML achieved these goals. Intel was the first chip manufacturer to invest in ASML on a very large scale. They were soon followed by TSMC in early August and Samsung in late August.

Table 4: Investments into ASML (Source: Hexus, 2012)

Company	*Intel*	*TSMC*	*Samsung*
Investment in stock	15% for $ 3.1 billion	5% for $ 1.03 billion	3% for $ 630 million
Investment in R&D	$ 1 billion	$ 345 million	$ 345 million

In total, the three semiconductor manufacturers have invested $ 1.7 billion in ASML's R&D programmes. This capital will be used to fund R&D in two areas. The majority of the funding will be used for the development of EUVL and a smaller part for the transition from 300mm wafer manufacturing to 450mm wafer, which could also reduce the manufacturing costs significantly. The chip manufacturers absolutely need EUVL to extend Moore's Law, which posits that every 18 months the number of transistors on a chip should be doubled. To further extend immersion lithography would, as it currently seems, be prohibitively expensive. However, EUVL still faces significant problems: currently, chips cannot be produced at such a pace to make it viable for mass manufacturing. ASML will use the funding to accelerate the development of its EUV lithography system, but ASML was reluctant to entirely fund the development of the EUVL system and carry the whole development risk, as semiconductor manufacturers are expected to be the main beneficiaries of a successful development of EUVL, which would enable them to reduce the costs and increase the capacity of chips substantially. From the perspective of ASML, the additional funding was decisive to achieve a better risk reward ratio. From the perspectives of Intel, TSMC, and Samsung the funding was crucial because they desperately need EUVL. Furthermore, the co-investor programme will guarantee those chip manufacturers first deliveries of the lithography systems, which will give them a lead in process technology (Electronic Weekly 2012) and allows them to participate in the success of ASML via their shareholdings if the supplier succeeds. To sum up, Intel has been by far the most active chip manufacturer regarding individual gap financing, but very recently TSMC and Samsung have also become increasingly active.

6 Discussion: Towards a Network-based Approach to Financing Innovations under Extreme Uncertainty

A major contribution of this paper is that it addresses an empirically observable and relevant innovation management phenomenon at the intersections of the network and financing literatures, namely financing in networks. More specifically, we have shown that the development of the system technology EUVL faces uncertainty that is associated with the entire innovation system (see also Linden et al., 2000; Appleyard et al., 2008). Our longitudinal study shows that two forms of roadmap gap financing have been central to addressing the high systemic uncertainty in the development process of EUVL and encouraging suppliers to initiate and maintain their development efforts. That is, a collective and an individual approach can be used to finance suppliers of critical components that have not yet been developed: so-called roadmap gaps.

Both approaches can be considered as forms of networked financing. The reason collective gap financing is considered a form of networked finance is obvious, as several organisations must pool their resources to fill critical gaps. However, as long as individual gap financing falls short of an acquisition (the hierarchical equivalent), it can also be considered a networked form of financing because the underlying rationale is to reduce the exposure of each participant in the innovation network by filling critical gaps. In both cases, financing practices target the level of the whole network.

In what follows, we first discuss the generalizability of our study before presenting and discussing some propositions based on our findings. As already mentioned above, the semiconductor manufacturing industry is special in several respects: a long-established research consortium such as SEMATECH is uncommon in virtually all other industries, the development costs and the systemic uncertainties involved are extremely high, and instances in which only a single supplier is potentially able to develop an essential component in a system technology are rare in most industries. However, there are also several commonalities between the semiconductor manufacturing and other CoPS industries (Hobday, 1998), such as their multi-technology and multi-component character and the importance of inter-organizational relations for the development process. To check the generalizability of our findings, we compare the semiconductor manufacturing industry with the aero-engine industry, a CoPS industry that is particularly well-researched. In Table 5, we highlight both the commonalities and differences between these industries.

Table 5: Commonalities and contrasts between the semiconductor manufacturing industry (based on our empirical data) and the aero-engine industry (based on previous research and our empirical analysis)

Industry characteristics	Semiconductor manufacturing industry (related to EUV)	Aero-engine industry	Degree of Commonality
Technological diversity, number of components, and specialisation of supplier base	Very high. Various fundamentally different technologies, such as optics and chemistry, are involved; a lithography system consists of thousands of components; extremely high specialisation of supplier base.	Very high. Various technologies, such as tribology and aerodynamics are involved (Brusoni et al., 2001); aircraft engine consist of up to 40,000 components; high specialisation of supplier base (Prencipe, 1997).	Similar
Interrelatedness of sub-systems and components	Very high. Sub-systems, such as power source and resist, are strongly interrelated; hardly any standardized interfaces.	Very high. Sub-systems such as the fan, compressor, and turbine systems are strongly interrelated; few standardized interfaces (Prencipe, 1997).	Similar
Costs for R&D	Extremely high. The development of EUV costs several billion dollars.	Very high. The development of a new engine costs up to 500 million dollars (Buxton et al., 2006).	Relatively similar
Uncertainty regarding success of development	Very high. Considerable risk of failure of development programmes.	High. Significant risk of failure of development programmes (Brusoni and Prencipe, 2011).	Relatively similar
System integrator	Lithography systems manufacturers and, to a larger extent, semiconductor companies (the customers) coordinate the R&D process.	Engine manufacturers coordinate the R&D process (Prencipe, 1997).	Different (but also some similarity)
Competitive rivalry	High. Three players operate in this market.	High. Three dominant players operate in this market (TIMES/Rolls Royce).	Similar
Power of suppliers	Medium/high. For some components/sub-systems only a single supplier worldwide is potentially able to develop them	Limited power. Result of rigorous adoption of dual sourcing strategies by engine manufacturers; some powerful suppliers, but for each component there is more than one supplier (TIMES/Rolls Royce).	Different
Power of customers	Medium power. Low and decreasing numbers of potential buyers of EUV; however, many of the potential buyers absolutely need EUV, which reduces their power.	High power. Low and decreasing numbers of potential buyers of new aircraft (TIMES/Rolls Royce).	Different
Threat of entry	Very low.	Very low (TIMES/Rolls Royce).	Similar
Threat of substitution	Very low.	Very low (TIMES/Rolls Royce).	Similar

Extant research (Prencipe, 1997; Brusoni and Prencipe, 2011; Brusoni et al., 2001) and media analysis show that, on the one hand, the aero-engine industry is similar in many areas to the semiconductor industry. Aero-engines and lithography systems both involve heterogeneous technologies and consist of thousands of components. In both industries, the R&D process is very cost-intensive, the competitive rivalry high and the threat of entry or of substitution low. Furthermore, there is always a significant risk that development programmes will fail, although this risk is higher in the semiconductor industry, in which, following the uncertainty typology proposed by Appleyard et al. (2008), it seems unclear more often, not only whether the specifications can be met within the bounds of cost constraints (performance uncertainty) or the life of existing technologies can be extended (pre-emption uncertainty), but also which firm will coordinate the innovation effort (leadership uncertainty) and whether a critical mass of customers for the new technology will develop (adoption uncertainty). In addition, the power of suppliers in the aero-engine industry seems to be significantly lower than in the semiconductor manufacturing industry. This is due to the fact that in the former industry there is more than one supplier for each component, while in the latter industry only a single potential supplier exists for some critical EUVL components. This constellation, and the fact that several semiconductor companies (customers and system integrators), absolutely need EUVL in the near future, increase the power of critical key suppliers. This power is evidenced by the fact that SEMATECH had to form a new consortium (EMI) to be able to fund Zeiss's development of the critical tool. As a result, the nature of inter-organisational risk-sharing agreements is quite different across these industries: in the semiconductor manufacturing industry the system integrators reduce the financial risk of suppliers to make them develop critical components, whereas in the aero-engine industry the suppliers buy stakes in the development programs of engine manufacturers to reduce the manufacturers' risk and to strengthen their position as key supplier.

However, there are strong indications that the aviation industry, and as a result also that of aero-engines, will face considerable challenges and could become more similar to the semiconductor manufacturing industry in the not so distant future. For instance, in 2007 the International Air Transport Association (IATA), an organisation representing the global airline industry, formulated the objective to achieve carbon-neutral growth by 2010, which "can only be met if the industry and governments jointly achieve infrastructure and technology advances" (IATA, 2009, p.2) and to build a zero-emission aircraft by 2057. Investment in technology – to develop radically new engines or biofuels – is considered crucial to reduce emissions at this scale. For this purpose, IATA has developed a technology roadmap to identify a range of innovative technologies such as new engine architectures and composite materials. This demonstrates that the aviation industry, similar to that of semiconductor manufacturing equipment, is globally organized in networks strategically led by manufacturers and aims collectively to achieve a technological leap (in terms of emission reduction; see also The Economist, 2011). As these targets are extremely ambitious, the probability increases that for some areas only a single supplier will be potentially able to develop specific components/materials. Similarly, these suppliers might be reluctant to invest aggressively in radically new and highly uncertain technologies. If this scenario materializes, the aviation/aero-engine industry would face challenges very similar to those of the semiconductor manufacturing industry today, and collective and individual forms of roadmap gap financing could become much more relevant for the industry.

Furthermore, SEMATECH has also become involved in other CoPS industries. In 2011, the US Department of Energy awarded $ 62.5 million to SEMATECH to launch and manage the Photovoltaic Manufacturing Consortium (PVMC). This is related to the SunShot Initiative of the US Department of Energy, which aims at reducing the cost of solar energy systems by 75% over the next decade. This indicates that the photovoltaic industry is facing challenges that are similar to those in the semiconductor industry. If we also take into account that there are general trends in CoPS industries towards an increasingly complex and specialised knowledge base and towards increasing development costs, it seems likely that in the future more of those industries will be confronted with the challenge of suppliers being indispensable for the development of components but reluctant to initiate the development because of high systemic uncertainty and the potentially negative effects on their financial performance. Thus, we argue that the results of our study are relevant beyond the semiconductor industry.

Theorizing from our findings in the semiconductor manufacturing industry and the comparison with CoPS industries, we submit that implications can be drawn for future research and other industry settings; not least for other CoPS industries. Towards this end we introduce four propositions, for which Figure 4 provides an overview.

Insert Figure 4

To enable the identification of a roadmap gap and the addressing of this gap by individual and collective roadmap gap financing, the existence of an industry-wide accepted roadmap is essential. This does not need to be the only relevant roadmap in an industry (e.g., there are several roadmaps in the semiconductor industry), it is merely necessary that one roadmap is dominant in a particular area (e.g., the EUVL roadmap for post-optical lithography). Without a technological roadmap that is – as a practice – backed by the industry, suppliers have hardly any incentives to engage in the development of a new technological option, because of the extreme uncertainty whether the system technology development will ever succeed. The example of the semiconductor industry and EUVL shows that the establishment and acceptance of a dominant technological roadmap can be driven by a lead firm or network orchestrator (Dhanaraj and Parkhe, 2006). Together with other companies Intel started the EUV LLC, in which Intel was the majority shareholder, to achieve a proof of concept. Its breakthrough helped to establish EUVL as the dominant technological option for post-lithography, which also made it more interesting for suppliers. Furthermore, Intel initiated the launch of the IEUVI, which monitors the global EUVL development process and identifies gaps in its roadmap. Hence, we suggest:

Proposition 1: *The more a lead firm supports the development of one of several competing technological options to achieve a technological proof of concept, the more likely it is that an industry will focus on a particular technology roadmap, which is a necessary precondition not only to identifying but also to financing roadmap gaps.*

Once an industry has agreed upon a specific roadmap and gaps that need to be closed (not least ensuing from individual firm efforts as highlighted in the previous proposition), collective roadmap gap financing becomes a viable option. Collective financing via a collaborative constellation (e.g. the SEMATECH consortium) becomes relevant when critical tools or technological components are in danger of not being developed because the development is very cost-intensive and risky and the respective market is too small to generate an acceptable profit. Individual roadmap gap financing is not attractive for single firms when financing is neither financially attractive, nor offers any other strategic advantage, which is why collective financing is more likely to occur. A case in point is metrology tools. Because the market is very small, high financial returns are unrealistic. Another strategic advantage is also difficult to gain for a lead firm: if a market is very small, the product is not used for mass manufacturing and the competitive advantage for mass manufacturers in process technology gained by early access is most likely insignificant. We cannot rule out that if a tool/component is essential for a system technology *and* the required financial support is beyond the threshold of what a consortium (particularly a multi-technology consortium) is able or willing to fund, one or a few lead firms will step in, too. With regard to EUVL, lead firms would have probably also engaged in individual gap financing of the lithography system supplier ASML if this financial deal had not offered a significant financial return (proposition 3a) or a strategic advantage (proposition 3b), because they need this technology urgently. Our point, though, is that if the financing of a gap neither offers a significant financial return nor a competitive advantage, firms will at least try to resort to collective forms of finance. Thus, we propose the following:

Proposition 2: *The less willing any supplier is to develop a critical tool or component for a system technology because the market is too small to be financially attractive, the more likely is a collective financing approach.*

As for individual roadmap gap financing, an organization – not least a lead firm – is willing to invest in a supplier if this promises a significant return on investment (Chesbrough, 2000; Gompers, 1995; Lindsey, 2008). This is also supported by our case study, in which three lead firms invested in EUV suppliers once a return appeared likely.[5] Intel invested via its CVC entity in four suppliers, and there are indications that these investments have been financially rewarding. This is corroborated by the fact that Intel Capital only invests if independent venture capitalists, which are measured by the financial performance of their funds (Harding, 2002), are willing to co-invest. Interviews showed that even if EUVL ultimately failed, Intel Capital's portfolio firms Nawotec and Media Lario would be interesting from a financial perspective, because they can also apply their technologies to other areas. Furthermore, the

[5] Primarily, the observed investments took the form of shareholder investments (e.g. Intel, TSMC and Samsung engaging in Intel), but other forms of finance such as warrants, loans, or other venture-capital mechanisms may be also possible (see also Golda and Philippi, 2007).

fact that Intel Capital was able to realize a trade sale of XTREME after only two years and of Nawotec after three years also indicates that these investments were financially attractive.

Apart from this, the lead firms Intel, TSMC and Samsung invested in the leading lithography system supplier ASML to speed up the EUVL development. But an additional motive may have been that, by becoming shareholders of ASML, these firms can realize financial gains via the rising prices of their shares, which could be substantial. If ASML succeeds in the development of EUVL, it will dominate this market and its share price will soar. Thus, we propose as follows.

Proposition 3a: *The more financially attractive the funding of a company critical for the roadmap is, the more a lead firm can be expected to finance gaps individually.*

Apart from purely financial opportunities in the form of a return on investment, gaining a strategic advantage can take the form of early access to new products, commercial benefits on products, or royalties on marketed products. In our study we observed this phenomenon with regard to Intel investing in joint development projects with the source supplier Cymer and two mask material suppliers (Golda and Philippi, 2007; I-84/Supplier). Intel's joint development projects with two mask suppliers are surprising to some extent, because SEMATECH also supported suppliers in this area. An interviewee mentioned that suppliers are sometimes sceptical about such collaborations, because Intel insists on arrangements that have a significant constraining effect on the managerial discretion of companies (I-84/Supplier). Possibly, the mask blank suppliers supported by SEMATECH were not willing to agree to Intel's terms and preferred SEMATECH.

Apart from that, the development agreements of Intel, TSMC, and Samsung with ASML, which were combined with huge equity investments, were not only driven by those companies' need to introduce EUVL into mass manufacturing and by financial incentives.

They were also driven by the fact that the financial deals with ASML will provide those companies with a significant strategic advantage, because they will get earlier access to ASML's EUV lithography systems than their competitors. This will give them a leading position in process technology over their competitors (Electronic Weekly, 2012). Hence, we suggest the following:

Proposition 3b: *The more the funding of a supplier critical to the roadmap provides a strategic advantage, the more a lead firm tends to engage in individual gap financing.*

7 Concluding Remarks

This paper started with the observation that the financing of innovations in inter-organisational networks in connection with critical suppliers has been neglected by the finance and the management literatures, although this issue is likely to be relevant to the development of complex system technologies in which the level of uncertainty is extremely high, but also to innovation networks more generally. While the management literature in general and network research in particular has thus far ignored the importance of the financial dimension of innovation by and large, the finance literature does not pay much attention to the inter-organisational dimension of the problem. To fill the resulting research gap in the future, we suggest – based on our literature review and our explorative study of the semiconductor manufacturing industry – that both an individual and a collective approach to financing 'uncertain networks' in the form of filling roadmap gaps can be relevant. Herein we contribute to prior research on innovation networks and financial management not only by identifying and clarifying these two approaches, but also by revealing under what conditions they are used.

Our study has several limitations. First, this case study only focused on a single lithography technology (EUVL), which limits its generalizability. Second, our knowledge about many funding decisions regarding EUVL roadmaps is limited, not least because this is a very sensitive area from the perspective of firms. Third, we analysed only one area of the SEMATECH industry roadmap – lithography – and did not analyse other roadmap areas, such as front-end process technologies. Fourth, the industry context is extreme in some respects (e.g. its capital-intensive and highly uncertain nature), making generalisations additionally difficult. The highly specialised supplier base and the existence of established co-financing mechanisms by consortia are further peculiarities to this industry, also limiting the external validity of the study. However, we have shown that roadmap gaps have also to be dealt with in the case of other lithography technologies, such as immersion lithography, and for other gaps in the SEMATECH roadmap, such as front-end technologies (also in the form of funding competing technological concepts). We even argue that our findings are at least partially generalizable beyond this particular industry context for at least four reasons. First, other pre-competitive and basic research and development consortia also share development costs and face technological uncertainty (e.g. CERN or the Diabetics Genetics Initiative). Second, roadmapping is conducted in other industries as well and seems to be gaining in importance (Phaal, 2011).Third, other industries are also likely to consolidate in a similar fashion to the semiconductor industry, where the number of key manufacturers and suppliers has declined over the past two decades due to financial and competitive pressures (Deans et al., 2003). Fourth, CoPS industries such as the aero-engine/aviation and the photovoltaic industry have important commonalities with the semiconductor industry. For these very reasons, the solar and automotive industries, among others, are orienting themselves on SEMATECH as a role model.

This study can only be regarded as a first step towards a theory on the financing of innovations in inter-organisational networks facing extreme uncertainty. One fruitful avenue could be to focus on other CoPS industries, e.g. satellite systems or rail transit systems, to evaluate whether the forms of networked financing described in this case also play a role in these industries. If so, researchers should explore the extent to which the propositions formulated in this study can be confirmed. In this respect, researchers could also analyse whether a combination of collective and individual gap financing is the norm or the exception in industries in which suppliers critical to the development of system technologies are financially supported. Finally, explicit theories might be worth employing to refine our observations. In any case, it appears beneficial to research further into networked financing in order to generate additional insights for research policy, managerial practice and theorizing, making us better able to deal with this timely and relevant phenomenon.

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