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**Path-Creating Networks in the Field of
Next Generation Lithography: Outline of a Research Project**

Funded by Volkswagen-Stiftung

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Introduction

The production of semiconductors has developed into one of the pivotal industries for advanced capitalist economies (Langlois & Steinmueller 1999; Buss & Wittke 2000). Yet the present systems of photon lithography – the basic production technology for semiconductors as an enabling technology – face technological and commercial limits. Hence, the next generation of production technology is called for, implying sooner or later a break away from the current technological path in order to meet the constantly increasing needs of the computer, telecommunication and many other related industries. Breaking with the present technological path, however, will only be possible, if an alternative technology is developed into a whole new manufacturing system feasible for large-scale production of ever more powerful chips.

At present, players in the global semiconductor industry including firms such as chip manufacturers, production system integrators and their subsystem suppliers as well as research institutes and government agencies still try and will continue trying to extend current systems by introducing enhancement technologies for photon lithography. However, these players realize that new technological paths should be in the making. One path-in-creation appears to be favored already to offer a radically new production system – according to industry reports and the experts we interviewed: extreme ultraviolet lithography (EUVL). Its realization seems feasible provided that a number of technological and commercial hurdles can be overcome. Although all key actors are engaged in this path, there is at least one other technological option from a range of possibilities that some players work on and which cannot be neglected: electron projection lithography (EPL). In sum, at least three alternative technological options are in competition with each other: the prolongation of the current photon path through enhancement technologies and two alternative solutions of next generation lithography (NGL), i.e. EUVL and EPL.

The extension of the existing solution beyond the long foreseen absolute limits of technological and economic viability as well as, in particular, all the conceivable new technologies of NGL require intensive and extensive collaboration between the players involved in processes of research and development. NGL solutions are based on highly specialized but interdependent subsystems which need to be developed simultaneously and integrated, if they are to be combined into an efficient production system that can serve the semiconductor markets of the future. Interorganizational collaboration in R&D networks constituted by actors from industry, research and government has already been practiced for about twenty years within and, notably, across the triad U.S., Japan and Europe in several national and supranational

consortia, numerous joint ventures and alliances, industry associations and some public-private partnerships.

Enormous investments are necessary and the risks are high, especially if it turns out – as many experts expect – that only one of the possible technological paths for volume production of semiconductors will prevail in the long run. Sharing and reducing such risks gives another reason for why the organization of innovation in networks is likely to persist and even expand in this field. It will be reinforced by the necessity to coordinate agents from different scientific backgrounds (optical physics, electronics, chemistry) as well as from different societal spheres (science, business and government) and from many different organizations. To what extent, under which conditions, and in which ways network organization can actually enable the creation of a new technological path in this field is far from obvious and, therefore, the main research question for this project.

The next section gives a summary overview of the theory of path dependence which has very recently been complemented by the concept of path creation. The relationship between path dependence and path creation is still debated in the literature, but we present our preliminary gradualist conceptualization developed in a preparatory study for the research project outlined here. Then we will introduce the empirical field of study, i.e. the development of NGL for semiconductors with particular reference to the different technological paths that have been considered as viable.

The development of NGL itself – as has been recognized by industry and further confirmed in expert interviews during our preparatory study – appears to depend not only upon technological innovations, but to a significant degree also upon social innovations such as interorganizational networks. This form of coordinating economic activities is introduced in the section that follows the presentation of the technological alternatives in the field of NGL. Moreover, interorganizational networks are discussed with respect to their potential for path creation, though only some preliminary insights can be presented here.

Having set the scene, we present our specific research questions, research design and methodology. Overall, the project will connect the scientific discourses on interorganizational networks, path dependence and creation, and technological innovation more closely and empirically. In addition, these contributions will enhance managers' and politicians' understanding of the conditions and processes of the development of new technological paths in a national and international context, which is required for policy action in vital areas of the economy and society.

Path Dependence and Path Creation in the Process of Technology Development

The concept of path dependence (or, path dependency) was first developed by David (1985) and Arthur (1989, 1990) in order to explain why certain technologies are used widely and even predominantly despite the fact that they would seem suboptimal in terms of technological and/or economic efficiency. Conventional microeconomics would fail to account for the persistence of such technologies and rather predict that they will be superseded by superior technologies. Yet, there have been prominent examples such as the QWERTY keyboard and VHS video that represent technologically suboptimal but nevertheless dominant paths. In contrast to microeconomics, the concept of path dependence can offer a comprehensive explanation for this phenomenon. According to economists like David and Arthur, path dependence is a self-reinforcing process beyond the control of the agents. Small events may trigger such a path. It is subsequently sustained primarily by increasing returns with the effect that once

there is at least some momentum the path enters into irreversibility. Thus, history matters: Out of several feasible technological options, it is not necessarily the most efficient path that prevails, but rather the one that gets adopted early – even by chance but always beyond the control of individuals or collectivities of actors – and then reinforces itself through increasing returns and lock-in effects.

Increasing returns may be caused, on the supply side, by economies of scale, sunk costs, expectations, learning effects and coordination costs. On the demand side, customs, conventions, norms, standards and network effects matter most. Indirect network effects are increasingly important in industries which, like the field of NGL, are characterized by system technologies. Because of increasing returns caused by these and other factors, the development of these technologies is surely not only “past-dependent but path-dependent” (Antonelli 1999).

While the argument of increasing returns is deeply anchored in economics, particularly in evolutionary economics (Nelson & Winter 1982; Witt 1997) and neo-institutionalism (North 1990), it connects well with social science research on innovating, organizing and networking. For instance, organizational sociologists emphasize the “isomorphism” (DiMaggio & Powell 1983) or “structural inertia” (Hannan & Freeman 1984) of institutions and – following Durkheim and Polanyi – the more general institutional “embeddedness” (Granovetter 1985) of all activities. “Cognitive and normative lock-ins” (Grabher 1993) receive some attention in socio-economic geography, while concepts like “imprinting” (Stinchcombe 1965), “absorptive capacity” (Cohen & Levinthal 1990) and “path dependence of knowledge” (Nooteboom 1997) are highly relevant in any discourse on technological and social innovation and offer organizational and/or institutional explanations of path dependencies.

Path dependence may be attributed to organizational forms, institutions, regions, fields and practices (e.g. Krugman 1991; David 1994; Braczyk & Heidenreich 1998; Pierson 2000; Ackermann 2001; Schreyögg et al. 2003) and, like organizational routines (Cyert & March 1963; Nelson & Winter 1982) and institutional contexts (North 1990; Powell & DiMaggio 1991; Whitley 1992), they are also highly relevant for the constitution of technological path dependencies in the form of “technological paradigms” (Dosi 1982) and “dominant designs” (Anderson & Tushman 1990). The path dependence of organizational forms, institutions, fields and practices is also caused by increasing returns, although the actual sources of these returns may be different from those typical for technology (Ackermann 2001).

Although the concept of path dependence explains plausibly some phenomena that were previously unaccounted for, it has been criticized for being over-deterministic. It looks at a process from the outside, focusing only on apparently inevitable self-reinforcing mechanisms, and it excludes the possibility that strategic action on the part of actors within the path can actually shape the path and even cause a break away from the path.

Recently, the concept has therefore been supplemented by the idea of path creation. Path creation, according to Garud & Karnøe (2001, p. 6, referring back to Schumpeter 1942), implies that “entrepreneurs may intentionally deviate from existing artifacts and relevance structures, fully aware they may be creating inefficiencies in the present, but also aware that such steps are required to create new futures. Such a process of mindful deviation lies at the heart of path creation.” Thus, while the concept of path dependence restricts strategic action to the exploitation and – consequently – stabilization of the existing path, the concept of path creation emphasizes the role of agency without neglecting structural and institutional features (of innovation processes). The self-reinforcing process governed by increasing returns, significant momentum and some irreversibility typical for path dependence is equally highlighted, but in Garud and Karnøe’s approach it is portrayed as something that is constituted by actors. Crucially, this view includes the perspectives and activities of insiders and it also implies that organizing for path creation is possible, for instance by translating ideas, breaking frames,

mobilizing resources, building powerful collectives and negotiating rules or generating momentum into a new direction.

In recognizing agency, the way path creation bears out in practice can be expected to vary. For instance, in their comparative study of the Danish and the U.S. wind turbine industry, Garud & Karnøe (2003) identify two different approaches to path creation: “bricolage” in Denmark and “breakthrough” in the United States. It also becomes clear that path creation involves an interplay of agency and structure. Garud & Karnøe (2001) make reference to Giddens’ (1984) concept of “duality of structure” which conceives structure as an outcome as much as a medium of action. From this perspective, technological objects, relevance structures, and even the possibility to create (or to destroy) increasing returns is endogenized into ongoing social practices of more or less knowledgeable and powerful agents.

While the concepts of path dependence and path creation are analytically quite distinct and to some extent at opposites, processes of technological development in the field of NGL could display features of both path dependence and creation. First of all, we propose that the notion of a ‘path’ of technology development contains the important assumption that it is difficult but not impossible for actors to leave or break such a path, thereby attempting to create a new path (Windeler 2003). Moreover, actors can deviate mindfully from ongoing processes that do not necessarily have the properties of a ‘path’ (yet), potentially also leading to ‘paths-in-creation’.

In principle, the possibility of path creation exists independent of whether or not a previous path or non-path process emerged ‘behind the back’ or through strategic actors’ deliberate efforts. If it exists, however, according to Garud & Karnøe (2001) effective path creation efforts require both “mindful deviation” and the mobilization of sufficient momentum by organizing “collective entrepreneurship”. In other words, path creation needs to be organized in a process of “reflexive structuration” (Ortmann et al. 2000) and is undertaken most effectively by actors who are knowledgeable, powerful and are already or become through their collective activities strategically placed, using their position to generate complementary efforts within a network of relevant actors.

Such efforts by the ‘path creators’ need to be sustained over time. The path-in-creation needs to be shaped continuously as the new technological field emerges. In successfully creating a path of technology development, the technological innovation as such is only one element. Actors, mostly in coordinated and cooperative efforts with other actors, strive to significantly influence in a path-reinforcing way all the dimensions of the relevant “organizational field” (DiMaggio & Powell 1983; Leblebici et al. 1991). In particular, they intentionally and reflexively seek to shape:

1. the constellation of (inter-)organizational actors who directly or indirectly sustain technology development through, for example, organizing R&D consortia, networks, focus groups, investors, etc.;
2. the technologies as such through, for example, building prototypes, developing measurement and testing equipment, or bringing together representatives from different firms and professions, e.g. for funding feasibility studies;
3. the relevant (state) regulations or technology regimes, for example for cooperation in R&D or for pre-competitive funding of R&D activities in particular fields to bridge the gap between basic research needed in the innovation process and industrial use; and last but not least
4. the practices, for example, diffusion of ‘best practices’ or creating commitment to technology options.

Path creation can take place by successful attempts at shaping one of these dimensions or any combination across them. The empirical effectiveness of path creating efforts can be assumed to vary between the four dimensions of organizational fields and between technologies.

Another important assumption is that, in a relevant organizational field, parallel and competing path creation efforts are to be expected, i.e. (the same) actors usually – at least for some time in the process of technology development – see more than one promising alternative to the current path. With regards to technology development, as a result, a range of (radically) different technological options may be conceivable, each of which is favoured as the future path by different actors and especially by their respective ‘path creators’. One further result, however, is that actors may be reluctant to lay all eggs into one basket and instead get more or less actively involved in several ‘paths-in-creation’ which are not yet paths. In other words, activities have to be qualified with regard to whether the actors are simply betting on an option or undertaking significant efforts at “mindful deviation” and “collective entrepreneurship”.

Beyond changes in the strategic orientations of individual and collective actors in technology development, the momentum required for effective path creation is difficult to generate insofar as it is likely to be confronted with inertia and resistance to change and with the struggles between different constellations of actors striving to realize their favoured options under the conditions of particular fields. Path creation is therefore an unpredictable and risky affair due to competing options and interests. The ‘old’ path, different strategic orientations and structural features of organizational fields discourage mindful deviation, especially when it is (still) unclear which of several possible ‘new paths’ will prevail. Path creation efforts by individual actors, even strategically placed ones, very much resemble the only partially effective steering efforts by riders on a ‘juggernaut’ (Giddens 1990, p. 139).

It remains difficult empirically to judge whether a particular process of technology development is path dependent or actively created. In fact, it is wise to assume that any path that we can identify in empirical work will contain elements of both path dependence and path creation (Windeler 2003). We therefore propose to use a gradualist understanding, analysing indicators of both path dependence and path creation, and comparing them to see which form of technology development dominates (see Figure 1 below). Our gradualist approach has the advantage that it can also show changes over time, e.g. a path moves from ‘predominantly path creation’ to ‘predominantly path dependence’, and it allows comparison between paths, e.g. a path that is low on both dimensions and one that is high on both dimensions.

It will be a challenge for empirical work, though, to operationalize the indicators on the two dimensions. A hard and absolute numerical measurement scale will not be feasible. Instead a judgement will need to be made by researchers based on their own observations as well as on reported perceptions by respondents in the field, in order to reach a conclusion on the nature of a particular path at a specific point in time. Thus, a mix of subjective and quasi-objective indicators is required. A method combining iterative coding (akin to the procedures of grounded theory, cf. Strauss & Corbin 1990) and more quantitative network analysis seems appropriate. From our interviews with experts in the field of NGL, we believe that useful indicators for path creation and path dependence will be, for example, the impact of announcements made by strategically important actors (e.g. steering committees or their members) about technological developments and the impulses from events such as series of conferences or workshops (in which participation may be variable over time). Further indicators would be the foundation and life cycles of consortia but also simple press announcements and the responses they generate in the field, e.g. specific investments or voiced disagreement. Moreover, the development over time of relevant networks, consortia, associations etc. in terms of

size, density, multiplexity etc. could indicate path dependence and/or path creation respectively.

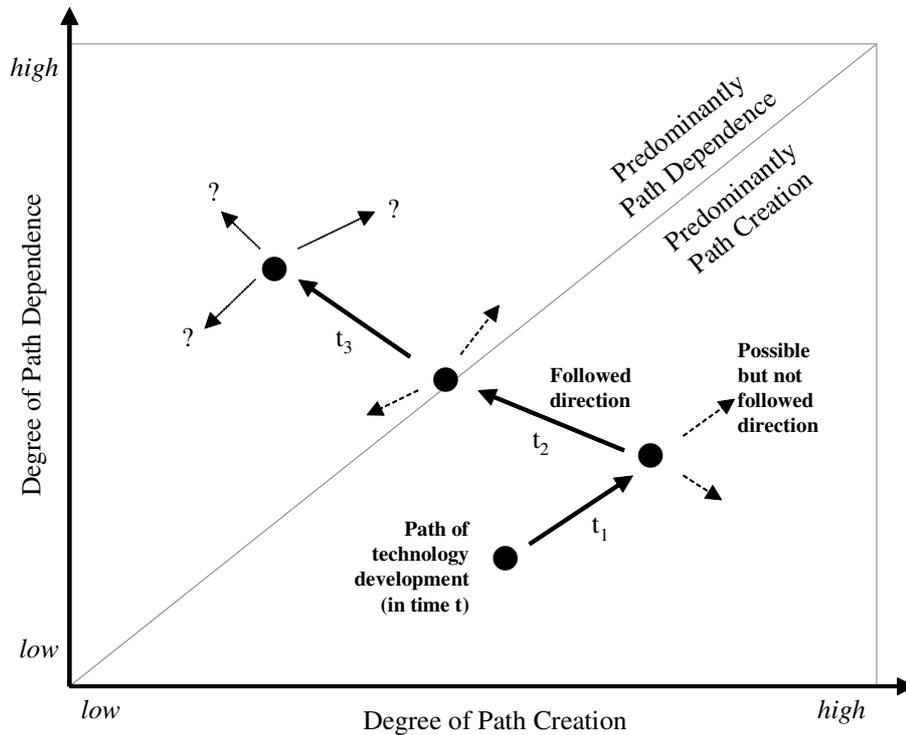


Fig. 1: Gradualist Perspective on Technological Path Development Between Dependence and Creation

From a structuration perspective, the operationalization of path creation and path dependence indicators can be informed fruitfully by Giddens' distinction between three recursively related dimensions of the social: signification, legitimation and domination. This means, for instance, that cognitive and normative understandings of innovation processes or technological paradigms and the related forms of resource usage have to be analysed within interorganizational networks or organizational fields. In addition, it needs to be explored whether sets of rules and resources are actively created by (a collectivity of) actors to deviate from an ongoing process or merely reproduced in a path-dependent fashion.

Moreover, structuration theory would require a look at different levels, i.e. firms, networks, organizational fields etc. and societal totalities like national innovation regimes. In this respect, our research will focus on a clear-cut set of social systems involved in NGL technology development processes: We will concentrate on the sets of rules and resources at the network level with special attention given to strategically placed actors in the field of NGL. This will allow us to investigate path-creating networks in their recursive interplay with the firm and field levels.

It needs to be acknowledged that the reflexivity of path dependence and creation practices is generally variable. However, in the case of extremely important technologies like NGL, we expect not only a relatively high degree of reflexivity within organizations, networks of firms and non-competitive consortia, but also attempts at organizing for systemic reflexivity with regard to technology development in the narrower sense and in the relevant organizational field. Nevertheless, we expect many network processes (and related organizational and field processes) to remain opaque for 'path creators'. For instance, tensions and contradictions re-

sulting from the fact that competitors collaborate in path-creating networks are likely to impact the possibilities of reflexive network management. The attempted and, eventually, realized degree of systemic reflexivity has to be established with reference to the three dimensions of the social, too, i.e. rules of signification and legitimation as well as resources of domination and with reference to the interplay of different societal levels (Windeler 2001, 2003). The structurationist conceptualization thus overcomes the one-sidedness of traditional microeconomic approaches to technological paths (which are blind to the role of power) as well as that of structuralist theories (which usually over-emphasize power without seeing it as embedded into cognitive and normative processes and actual social practices).

Since the theorizing and researching of path creation has only recently started, our understanding of its relationship with path dependence offers an important step forward but will need to be refined further in our project and in correspondence with other researchers. Despite the explicit reference of scholars in this field to Giddens' theory of structuration, the potential of this approach for clarifying the understanding of this relationship has not yet been fully utilized. The same is true for the role of interorganizational networks in this process of collective entrepreneurship, although some case studies clearly demonstrate that this form of coordination has much to offer for collective organizing (Garud 2002; Garud et al. 2002).

Even if not specifically related to the issue of path dependence and path creation, the study of interorganizational networks in general has been of major concern during the last decade or so in innovation research, organization theory, the study of technology, and regional economics. For instance, "networks of innovators" (Freeman 1991) have been on the agenda of research in these fields since firms started to outsource research and development in order to reduce the investments and risks involved, and to improve time-to-market (e.g. Camagni 1991; Kowol 1997; Rammert 1997; Duschek 2002). This research, like other streams of network research (cf. Gulati 1998; Sydow & Windeler 1998; Ebers 1999; Windeler 2001), has enhanced our understanding of the economic potential of this organizational form, of the importance of initial conditions and learning processes for network development, and of the needs, possibilities and pitfalls of reflexively managing this form in order to protect it from failure (Miles & Snow 1994).

On a somewhat more general, theoretical level, networks of innovators are often researched from the perspective of evolutionary economics (Antonelli 1999). Like research on path dependence, which has been much influenced by evolutionary thinking, evolutionary economics has paid little explicit attention to agency, although these approaches have never denied the capability of agents to act strategically (Winter 1987; Aldrich 1999; Kappelhoff 2000). Consequently, evolutionary economics – in contrast to some social theories – is not well-equipped to conceptualize the complex interplay between agency and structure. Nevertheless, useful insights of evolutionary theory (e.g. path dependence, trajectory, co-evolution) can and should be integrated into a more advanced and elaborated theoretical conception of path dependence and path creation on the one hand and of reflexive network development on the other. Structuration theory, with its explicit concept of agency and its theorem of the "duality of structure" (Giddens 1984), is certainly one of the relevant approaches to integrate these insights and to develop them further (cf. Bryant & Jary 2001 for an overview of the uses of structuration theory).

Next Generation Lithography – Enhancing the current Path vs. Pursuing Radical System Innovation

The necessity to create new technological paths in lithography is widely acknowledged, most prominently by major industry players such as Intel, AMD, Motorola and Infineon who are also involved in the process of continuous development of the highly influential International Technology Roadmap for Semiconductors (ITRS). In addition, studies like *Harnessing Light – Optical Sciences for the 21st Century* sponsored by the National Research Council (1998) of the U.S. have had a significant impact in the scientific and political sphere, including, for instance, the research funding policy of the Federal Ministry of Education and Research (BMBF) in Germany.

The general scenario captured by the ITRS and shared by most of the actors in the field is that by continuing to double the number of transistors on semiconductors about every 18 months (according to the so-called Moore's Law) by making the structures on the chip smaller and smaller, the present lithography technology will reach physical and economic limits before long (cf. Hürter 2003 for a critical review). Nevertheless, we can see that actors on the current path seek to extend it by developing enhancement technologies such as off-axis illumination, phase shifting masks, and optical proximity corrections. Immersion technologies (where a liquid amplifies the lens effect) are the latest invention, promising to make the current technological path based on well-known photonics and optics usable below the 65nm node. New 157nm light sources and new lens materials that are currently in development may even lower the physical and economic limit of the current path to 32nm on the chip. At any rate, we have been told by experts and could observe for ourselves that there are strong incentives for firms, especially the chipmakers, to stay on the current path for as long as possible.

At the same time, it is (still) recognized in the industry that a break away from the current path will be required, calling for the successive development of radically new technological options from current proof-of-principle devices, through alpha tools in 2005, first field tests at selected manufacturers in 2007, to the start of volume production in 2009:

„In 2001 and beyond, lithographers are confronted with two sets of challenges. The first is a consequence of the difficulties inherent in extending optical methods of patterning to physical limits, while the second follows from the need to develop entirely new, post-optical lithography technologies and implement them into manufacturing. Not only is it necessary to invent technological solutions to very challenging problems, it is critical that the costs not be increased because of the new methods“ (ITRS-L 2001, p. 1).

The “technological paradigms” (Dosi 1982) for NGL options are quite different. For instance, when extreme ultraviolet light (EUV) is used, the wavelength becomes so short that the light can no longer be transmitted through lenses, but instead needs to be reflected by mirrors, because the lens would absorb the light, and the process has to happen under vacuum conditions, because EUV light is even absorbed by air. Other technological options are equally radical, for instance, maskless technologies, given that to date the mask is a crucial (and expensive) component in the process. Like the present technology, the new options imply highly complex systems, but will be based upon an entirely new generation of technologies with some completely new components: xenon plasma or gas emission (as the EUV light source), condenser optics, mirrors (instead of lenses), new materials for chip masks, resists, and silicon wafers. Experts agree that all technological options for NGL imply the creation of a new technological path which will be characterized by artifacts differing radically from the existing ones. This holds major strategic and (inter-) organizational implications for all the actors involved.

The system character of any lithography technology means that innovating NGL not only involves integrating complex sub-systems and components, but also highly specialized knowledge from different disciplinary fields (optical physics, electronics, chemistry). It follows that specialized research institutes as well as some big and many small and medium-sized firms are strategically placed actors in the process of path creation for NGL. Moreover, a system integrator (like ASML in Europe, and Canon and Nikon in Japan) and several sub-system integrators (like Zeiss for the optical and Infineon for the resist technology in Europe) are needed for technological innovation which, thus, is likely to resemble a distributed innovation process coordinated by networks (Rammert 2000). In fact, innovating NGL, in the view of most actors in industry and research, seems to involve a significant degree of inter-organizational collaboration both nationally and internationally. In addition, once the system technology is in place, manufacturing and marketing is likely to take place in interorganizational networks, too. Overall, because of the huge investments necessary for creating a new path in this technological field, “closely coordinated global interactions among government, industry, and universities are absolutely necessary to narrow the options for these future generations” (ITRS-L 2001, p. 14). In other words, there is also the generally shared view that only one path can actually be developed to the degree that it can be used for volume production. At the moment, experts see extreme ultraviolet lithography (EUVL) as the most likely candidate, although many technological and economic obstacles still need to be overcome.

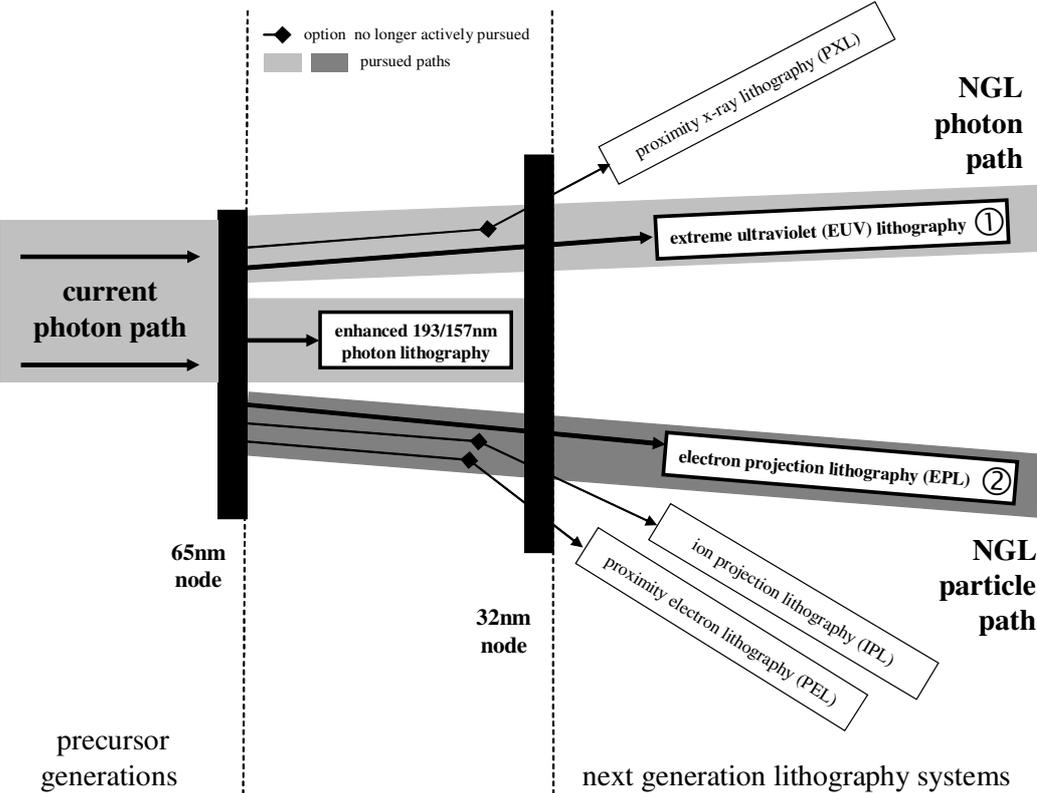


Fig. 2: Present and New Generation Lithography Systems

Figure 2 illustrates the present situation as it can be inferred from the literature, business press, conference proceedings and from the interviews we conducted. First of all, there is a strong drive, as stated above, to continue on the current photon path at least for a while. We

can see strong elements of path dependence here but also collective strategic action in the form of developing enhancement technologies on the present path. However, in sharp contrast to the NGL paths, experts expect that the current photon path has no future beyond the 32nm node due to currently unquestioned basic physical limitations. Second, there is the NGL photon path which is still related to the conventional photon path but operates at wavelengths and energy levels that are not comparable to the lasers used today. It necessitates innovation in practically all parts of the lithography system. This potential path was for a particular period of time made up of two main trajectories for volume production: synchrotron lithography (PXL) and EUVL, the latter of which has continued and become the favorite alternative. Third, another potential path captured for a while three technological options for volume production based on particles (instead of light): proximity electron lithography (PEL), electron projection lithography (EPL), and ion projection lithography (IPL). Further technological options, most notably maskless technologies, are also researched but are not seen at this point in time as contenders for volume production systems.

In fact, at the end of 2003, the industry was increasingly geared towards EUVL as the most promising path, being the most advanced out of the different trajectories and receiving more investment and support from major players than other contenders (see, already, OLE 2002). Interestingly, x-ray (or synchrotron) lithography was once considered to be the furthest developed option: “However, industry support for x-ray lithography appears to be waning primarily because of the difficulties encountered in making masks suitable for the geometries less than 100 nm” (Levinson 2001, p. 354). A major proponent of this technology, Canon, has (again) started to invest in the development of EUV technology.

EUVL currently finds the most support, not only in Europe and Japan but also in the U.S.. In March 2001, IBM, which already collaborates with Nikon in the development of EPL, announced that it is to join the EUV consortium made up of six important chip producers and strategically led by Intel (LaPedus 2001a):

„In spite of the technical challenges, EUV lithography has shown sufficient promise to be pursued as a successor to optical lithography. A consortium of several integrated circuit manufacturers – Intel, AMD, Motorola, Micron, IBM, and Infineon – have formed an EUV Limited Liability Corporation (LLC) to fund development of this technology, including the fabrication of a full-field exposure tool, the Engineering Test Stand“ (Levinson 2001, p. 346).

Two years later, the EUV LLC has already achieved its aim and provided the ‘proof of principle’ that EUVL is feasible, even if there are many unresolved issues left. At an EUVL Symposium in Antwerp in September 2003, the range of participants and their confidence in realizing EUVL has given impressive evidence for the momentum and “collective entrepreneurship” that this path-in-creation has already gained (IMEC 2003). At the same time, however, the target of 2007 as the year that EUVL could be used in volume production has been put back. 2009 is now the year that stepper makers such as ASML aim for. Experts tell us that, even in 2009, only the first full-scale systems will be installed at a small number of chip manufacturers. Nevertheless, some chip makers, especially Intel, strive to realize this option in order to stabilize their reputation for technological leadership associated with their brands (see Wittke 2003 for the changes in Intel’s strategic behavior over time). Besides strategic interests and initiatives in distributed innovation processes, this shows that the move to EUVL is still far from inevitable or irreversible, because important technological and economic issues still need to be resolved, but also because the current path and other new options continue to compete for resources. Being engaged in EUVL development is therefore still risky and a highly expensive “mindful deviation”. Since only one option will survive, according to the expectations of industry experts and announcements by the chip makers, strategic activi-

ties will not only affect relevant economic opportunities directly related to NGL but also beyond the path creation process.

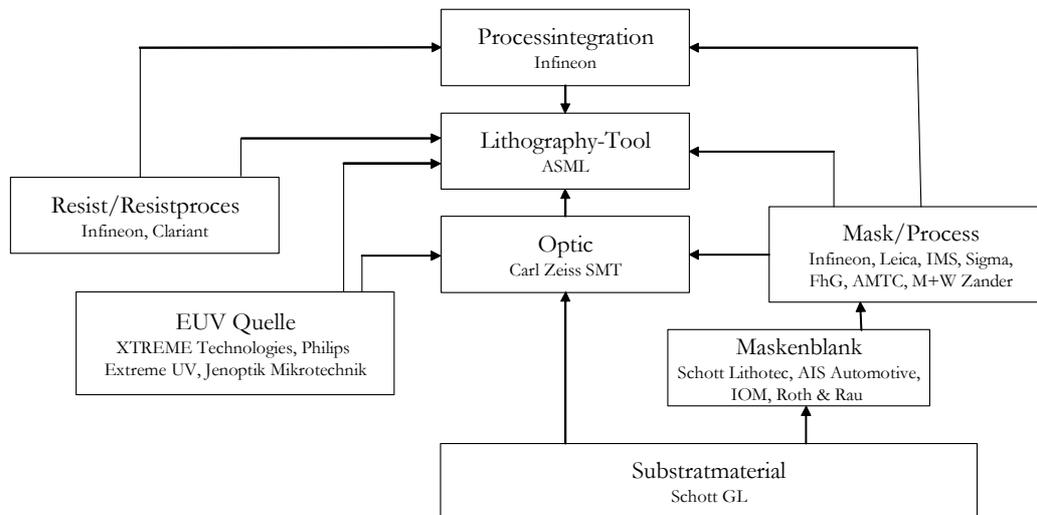


Fig. 3: The German EUVL Consortium (Aschke 2001, modified and updated)

In Germany, not least thanks to a funding program by the BMBF and initiatives by associations (such as the VDI), a German EUV consortium – closely connected to the Dutch firm ASML as the system integrator who, in the end, sells the steppers to chip makers – was formed at the end of 1999. Infineon, Zeiss and all the other current members of this consortium (Figure 3) sustain interorganizational relationships which go well beyond the membership status. For instance, Carl Zeiss SMT AG is in a strategic alliance with ASML, the world’s biggest manufacturer of lithography systems, to the effect that they are their exclusive supplier of optics. Through ASML, the German EUV consortium has gained access to Intel (LaPedus 2001b) which is of outstanding importance for the further development of this NGL path. In fact, most of the competitive subsystem suppliers for EUVL are located in Europe and particularly in Germany. ASML as a system integrator is also European but its main competitors, Canon and Nikon, are Japanese. And the actual buyers of lithography systems tend to be American chip manufacturers, first and foremost Intel, besides a significant Asian market. EUVL is therefore developed in the context of a global supply chain with a strong German-American axis from specialist suppliers through integrators like ASML to the big customers such as Intel.

Besides EUV lithography, two other options remain relevant: First, the enhancement of the current photon path; second, the EPL option. As Figure 2 shows, all other options have already been or are likely to be abandoned before the 32nm node. With regard to EPL, experts consistently state that this option is technologically feasible, but more limited in throughput so that for economical reasons it will be less usable for volume production. In the late 1990s, EPL was still seen as a strong competitor to EUVL, but major companies have decided in the meantime to divert their efforts away from EPL. For instance, ASML ended the SCALPEL joint venture with Applied Materials Inc. and Lucent Technologies in January 2001. Nevertheless, many companies are still working on EPL. For instance, Nikon collaborates with IBM to produce exposure tools: “With such development efforts, it is expected that a great deal will be learned about electron projection lithography over the next years” (Levinson 2001, p. 352).

The overall picture illustrates why, given the enormous investment necessary for NGL tools, actors in the field fervently spread the message that it is “absolutely necessary to narrow” the options down (ITRS-L 2001, p. 14). At present, the developers and supporters of the different technological paths outdo each other in announcing so-called alpha and beta tools for their favored paths. These tools are necessary predecessors to the production-ready system for the 32nm node now targeted for 2009. Those who are first are more likely to set the industry standard, attract most industry players and thus generate the degree of momentum and irreversibility necessary for sustainable path development.

The very few empirical studies of the organization of the optoelectronics industry to date (Miyazaki 1995; Hassink & Wood 1998; Hendry et al. 2000a, b; Hessinger et al. 2000) show that the research and development as well as the manufacturing of these technologies are in fact organized on an international scale, yet they are regionally concentrated:

„Following this pattern, the opto-electronic industry is now characterized by large numbers of high technology SMEs [Small and Medium Enterprises] concentrated in regional clusters and engaged in symbiotic relationships with multinational firms” (Hendry et al. 2000b, p. 132).

These SMEs develop and manufacture components. Some of them may even qualify as sub-system integrators. As such they are tied to the networks of relationships organized by the few global players in this industry which, like ASML and Nikon, act as system integrators. In the area of NGL, though, the relevance of regional clusters is seen by experts as less pronounced and we will need to investigate whether this continues to be the case when the new technologies become more advanced and move into production. Developing next generation lithography is clearly an international or even global game, but it may be no coincidence that some very strong suppliers are located in certain regions traditional for the industry.

Organizing for Path Creation: Reflexive Network Development

Organizations are highly relevant in modern societies (Perrow 1991) since a large proportion of social interactions take place in and are shaped by organizations. Organizations themselves should be seen as embedded in organizational fields. “Organizational fields”, according to DiMaggio & Powell (1983), “in the aggregate, constitute a recognized area of institutional life: key suppliers, resource and product consumers, regulatory agencies, and other organizations that produce similar services or products” (p. 143). It is important to recognize that despite the deterministic neo-institutionalist heritage attached to the concept of organizational field, it can be (and should be) opened up in order to embrace agency and entrepreneurship. Moreover, organizational fields need not be restricted to industries or geographical regions. Organizational fields can be issue-based (Hoffman 1999, Anand & Watson 2004). And the development of NGL can be seen as an issue around which a field is constituted in which different competing constellations of actors strive for their goal attainment and where the structures of the field are medium and result of their activities. Actors in the NGL field are sometimes global players and eventually involved in what we would call path-creating networks. These are defined as interorganizational networks, focusing on the creation of conditions that enable such networks to mindfully deviate from existing artifacts and relevance structures.

Interorganizational networks seem to be an increasingly necessary, even if not sufficient condition for the possible creation of new technological paths. This is particularly true in fields of complex system technologies like optoelectronics in general and NGL in particular. The experts we interviewed – who in their day-to-day responsibilities tend to be concerned with technological issues – clearly recognized the vital role of interorganizational networks

not only in coordinating dispersed and highly specialist simultaneous research and engineering, but also in gaining support and consensus on technological options. To some extent, networks of interorganizational relationships emerge from simple business transactions that intensify over time or happen to run into particular opportunities or challenges. However, networks can also be organized reflexively, i.e. actively and intentionally created and sustained, (re-)producing rules, resources and experiences strategically. The active creation of networks is increasingly sought by companies and also by government bodies in Europe, the U.S. and Japan – the German BMBF is no exception (see www.kompetenznetze.de). The latter offer financial support for the organization of interorganizational collaboration in the field of research and development, supporting regional clusters (e.g. the eight regions belonging to OptecNet Germany), but also – especially in the field of EUVL – national consortia (e.g. the BMBF-sponsored German EUVL consortium) and international programs (e.g., at the EU level, MEDEA+).

A perspective on reflexive network development, which is based upon Giddens' (1984) structuration theory, conceives managing interorganizational networks as developing networks actively and intentionally (Sydow & Windeler 2003). Although actors vary in degree and kind of reflexivity, management practices are usually based on a general awareness and knowledge of the structural possibilities and constraints of action in the particular context. The continually actualized knowledge basis is not only built up by reflexive monitoring and rationalization of network practices in organizational fields, but also by systematic comparison of the network form with alternative forms of coordination – i.e. with markets and hierarchies (Windeler 2001, p. 334). In their management practices, actors more or less reflexively refer to rules and resources of the network in order to influence these very structures in a way that increases network efficiency and effectiveness, or – in early phases of network development – simply renders interorganizational collaboration more stable (Sydow & Windeler 1998). Thus, the concept of reflexive network development overcomes both the deficiencies of evolutionary understandings which lack an explicit concept of agency and the shortcomings of interventionist concepts like “transorganizational development” (Cummings 1984) which by and large ignore the relevance of structures (Sydow 2001).

The reflexivity of these processes can, to some extent at least, be decoupled from individual actors and thus be institutionalized at the network level, the organizational level and/or even at the field level (Windeler 2001), as evidenced by the activities of the International Sematech consortium. Such an institutionalized reflexivity could then become “the very basis of system reproduction” (Giddens 1990, p. 38). Although more reflexivity does not necessarily mean more efficiency or effectiveness, in the area of interorganizational networking in general and in the field of developing NGL in particular we would, at least, put forward the proposition that more reflexivity in the network makes the creation and realization of a technological path more likely, because path creation implies “mindful deviation” in order to generate self-propelling momentum for “collective entrepreneurship” in an organizational field. Finally, more reflexivity implies that actors notice that interorganizational networks are not guaranteed to be flexible. Path-creating networks could develop cognitive and/or normative lock-ins, if not managed properly (Grabher 1993; Gargiulo & Benassi 2000).

There are several indications that the degree of reflexivity in developing interorganizational networks in the field of NGL is relatively high and still increasing. Experts confirm that companies and agencies continuously monitor the networking activities within and across the triads – especially by participating regularly, for example, in important conferences – and they take action in order to be associated with strong partners instead of competing on their own. Some experts, for instance, speak of the “ASML network” and the “Nikon network”, i.e. networks around key system integrators (cf. Brusoni et al. 2001), while their competitor

Canon apparently pursues a rather integrated model of research and development in the field of lithography. Most importantly perhaps, governments in Germany, the European Union and the U.S. are now much more conscious of the economic importance of interorganizational networking for innovating technologies. This is reflected in programs such as the BMBF's OptecNet and EUVL program. However, it is unclear to what extent and how such national initiatives take into account the fact that they already encounter, on the one hand, an intensively and globally networked technology-related field in which R&D consortia, joint ventures, industry associations, and public-private partnerships are the most visible organizational forms of collaboration. On the other hand, these forms of collaboration transcend national boundaries and the discretion of a single nation state or triad. (The fact that the success of the German EUVL consortium is heavily dependent on the Dutch system integrator ASML is a strong case in point.) At any rate, innovating NGL will be constituted in and through interorganizational networks which are at least partly able to use different contexts for their activities. Whether these are really path-creating networks is an important question that needs to be explored.

Specific Research Questions

Against the conceptual and empirical background outlined above, four questions will be at the center of our research project, which – in terms of theory – will be based on a structurationist reconstruction and clarification of the interplay between path dependence and path creation and the role of reflexive network development in the international context of innovating next generation lithography:

1. How is the creation of new technological paths in the field of NGL possible in the face of existing paths and their technological, organizational and institutional dependencies? In particular, which constellations of actors (including large industrial players and specialist suppliers, pre-competitive consortia and research institutes, trade associations and government agencies) as well as technologies, regulation and practices foster or hinder such a development?
2. What is the nature and the role of interorganizational networks and their more or less reflexive development in the evolution and creation of technological paths, i.e. what is the impact of social-organizational innovations on the process of innovating technology?
3. How can path-creating networks be identified and structurally characterized? In particular, how can they be understood in terms of origin, domain, membership, coordination, strategic leadership or – more generally – sets of rules and resources (re-)produced more or less reflexively by constellations of actors? How do they differ in the degree of embeddedness in technology fields and in the impact of these fields on technology development?
4. What are the implications of the national and international scope of path-creating networks in technology fields? In particular, how is technology development influenced by the fact that chip manufacturers as customers are primarily located in the U.S. (and Asia) while the suppliers of subsystems are European (and predominantly German) and the system integrators European (ASML) or Japanese (Nikon, Canon)?

The overall aim is, therefore, to enhance our understanding of organizing as a key factor in innovating technology across national, organizational and disciplinary boundaries. We will apply existing theory on interorganizational networks to the empirical field of NGL and thereby gain valuable new insights for both theory and practice that are highly relevant also

with respect to the interplay of the development of national societies and economies on the one hand and basic technologies at a global level on the other.

Research Design and Methods

Our research design is based on information about the status of NGL development which we have obtained through secondary sources such as conference proceedings and relevant business news but, most importantly, through in-depth interviews with 17 experts, including academics, agencies and practitioners, conducted in preparation for this project mainly in the second half of 2003.

We will study three distinct technological options in real time, but with different weight: extreme ultraviolet lithography (EUVL), 193/157nm enhanced photon lithography, and electron projection lithography (EPL).

First, EUV lithography is considered to be the most important technological option and the most likely path for NGL. Although experts are in agreement that the first EUVL systems for volume production will only be available in 2009 at the earliest (not in 2007 as scheduled in the ITRS roadmap in 2001) to a select group of chip manufacturers and that there are still major technological issues to be resolved, interorganizational activities and collaborative efforts in the area of EUVL have increased in 2003 and it appears that the success of various projects that prove the feasibility of EUVL is already generating considerable momentum. This path-in-creation will therefore receive the largest share of our attention.

Second, experts say that chipmakers in particular have an interest in continuing the known photon technologies for as long as possible through enhancement technologies. This could postpone further, and possibly even jeopardize, the introduction of EUVL. We will therefore investigate the efforts undertaken to extend the current 193nm path and its 157nm successor and analyze, if the continuation is due to path dependence or a kind of path creation aimed at preventing the emergence of a new path. Interestingly, we have noticed that some key actors, especially chip manufacturers and system integrators, are engaging in EUVL and photon path enhancements at the same time.

Third, EPL remains a technological option which in the late 1990s was still ahead of EUVL as the most promising candidate and is now perceived as a technology that, although still followed by some significant players, might be useable only for specialist niche markets. We will investigate the development of this path over time, but not as intensively as EUVL and the option of enhancing the current photon path. It will be interesting to reconstruct, though, how actors made their choices between EPL and EUVL, how the respective networks developed and gained or lost momentum. When we focus on EUVL, it should be possible to portray EPL in contrast.

In fact, it is far from clear which of the three paths that we focus on will be dominant by the time our project will be concluded, but we expect that our research design will enable us to present interesting findings on the fate of the current photon path, the successful new path and one path that looked strong but then did not prevail. Moreover, we will take the opportunity to explore why the other technological options (i.e. PXL, PEL, IPL; see Figure 2) failed to become a sustainable path.

Another central aspect of our research design is that innovating NGL is highly international and, specifically, suggests that we need to study, on the one hand, activities in the U.S. where the primary demand of the new technologies stems from the large chip makers such as Intel and others organized in the ISMT consortium and, on the other hand, the activities of subsystem suppliers in Germany (which dominate the European scene at least in EUVL). In

other words, innovating NGL happens along an international value chain in research and development and we will focus in particular on the coordination of activities between suppliers in the German EUV consortium, the system integrator ASML as a major link, and the key American customers. This will enable us also to explore the role of regional embeddedness of international networks both within countries as well as in regions of the global triad. We will analyze and compare the approach to reflexive network development taken by American firms and agencies in comparison to corresponding European actors. Experts have already told us that reflexivity is stronger in Europe but this needs to be investigated properly. Besides our focus on innovating NGL in Germany and the U.S., we will study developments in Japan with less intensity and resources, due to pragmatic limitations, focusing on system integrators (Canon, Nikon). We will seek opportunities to gather first hand insights on Japanese players and their networks.

Since our research approach rests primarily on structuration theory, a post-positivistic methodology is required (cf. Windeler 2001, pp. 138-140; see also Lincoln & Guba 1985) in our case applied to the study of the constitution of technological systems as well as to the study of network forms of organization. Generally speaking, we recognize that the phenomena we intend to study are essentially socially constructed by actors and we will commonly need to draw on subjective, qualitative sources, i.e. archival material and primary data from interviews and observations. At the same time, we operationalize our key concepts partially through quasi-objective indicators and quantitative methods, in particular structural network analysis (e.g. Wassermann & Faust 1994; Kilduff & Tsai 2003).

For instance, operationalizing our gradualist concept of path dependence and path creation, we will use indicators based on the subjective accounts that actors give about whether “mindful deviation” takes place, whether there is “momentum” and “collective entrepreneurship”, generated intentionally by strategically placed actors, or whether they see technology development as an essentially uncontrollable process driven by past decisions and immediate necessities. At the same time, there will be sources such as conference documentation and other reports where activities that could count as path-creating events can be identified more objectively and where, for example, changes in membership speak for or against the strength and network character of such activities. A similar logic applies to the concept of reflexive network development where it will be possible to obtain the direct accounts of the actors concerned, but also to observe more independently the level of coordination, monitoring and institutionalization occurring and/or the more dyadic or more multilateral (network) development approach taken. These indicators will enable us to assess the degree of networking and reflexivity underlying the process(es) of innovating technology. The further refinement of such indicators will be a primary task in the initial phase of our project.

We already know, however, that we need to gather comprehensive data on all the relevant actors, i.e. chip makers such as Intel, system integrators such as ASML, and subsystem suppliers such as Carl Zeiss SMT, Philips EUV, Schott Litho as well as agencies administering public funding and research such as the VDI-TZ in Germany. The data required can be obtained partly through archival material (including a wealth of information on the Internet) and surveys, but also more importantly through in-depth interviews. We have already interviewed a number of key actors who have not only offered to talk to us again in the future, but also to assist us in getting access to other relevant actors and data sources. Our experience from the preparatory study is that actors recognize the relevance of our topic and are prepared to talk openly about the topics we cover.

Apart from individual actors (i.e. organizations), we will gather similar data on the most important consortia, in particular International Sematech (ISMT), the EUV LLC, and the German EUVL consortium. Moreover, we will identify and analyze conferences and other

events (symposia, workshops, etc.) nationally and internationally which are relevant to the three paths that we focus on, the main priority being EUVL. This is where we see the greatest potential for applying structural network analysis to supplement our more qualitative approach.

In practical terms, our research will identify and analyze the key actors, events and themes in the process of innovating NGL in the period 2004 to 2009, reconstructing also the development of technological options since the first NGL Conferences in the mid-1990s. For the larger international context, it will be possible to construct actor-event matrices which can reveal the network character of technological innovation by showing which actors are related in which way to the key events that drive a technological option forward, for example the foundation of a consortium or the announcement that EUVL should be available in 2009 instead of 2007. For the German EUVL consortium, we plan to apply structural network analysis more broadly in order to reveal changes in the actor constellations over time.

Our use of structural network analysis will complement the in-depth interviews that we will conduct. We plan to have three waves of intensive interviewing, but will also conduct further interviews at other points in time in response to new developments in the field. Overall, we estimate that about 100 interviews will be conducted over five years. The majority of interviews can take place in Germany, but interviews in the U.S. (approx. 25-30) will also be essential. Since the development of NGL is truly international, interviews may also have to be conducted in other European countries and, in exceptional cases, in Japan. It is an advantage that the key players come together several times a year at conferences and other events, giving us the opportunity to attend such events in order to conduct pre-arranged interviews.

We already have significant experience in interviewing actors in the field of NGL and, in particular, EUVL. In the future, we will ask even more specifically about key actors, significant events and critical factors in the process, about the exact workings of the networks that actors are involved in, about the degree of reflexive network development, about the embeddedness in organizational fields, and about further points highlighted in this proposal. We will also obtain more categorical, quantitative data to be used in structural network analysis.

“Path dependency is an interdisciplinary concept” (Hirsch & Gillespie 2001, p. 71). Like innovation research in general, our research topic is not only located at the boundary of economics, management, political science and sociology, but also involves anthropology, and, last but not at all least, economic, social and technological history. Among these disciplines, economics and sociology stand out, since they also consider the possibility of path creation and since they both address organizers, managers and policy makers. The use of structuration theory, which emphasizes the social embeddedness of any economic activity and is used in management studies (e.g. Pettigrew 1985; Whittington 1992; Barley & Tolbert 1997; Duschek 2002; Pettigrew et al. 2003) as well as in the sociology of organization and innovation (e.g. Barley 1986; Orlikowsky 2000; Windeler 2001, 2003), guarantees an interdisciplinary and yet integrative research approach.

Researching the field of optical technologies also requires some knowledge of optical sciences. In terms of science and technology, this field of study is itself interdisciplinary and has its roots in optical physics, electronics and chemistry. Concerning these disciplines, we have connections with the leading Leibniz Institute which contributes to the emerging field of optical sciences in the Berlin/Brandenburg region. We have established direct contacts with several major firms and research institutes in the field and the managing directors of all OptecNet regions in Germany. We also have indirect contacts to relevant actors in the United States.

Although the research for the proposed study will need to be conducted in different countries, it will be carried out by a core team of German researchers in order to assure conceptual and methodological consistency but in close and intensive collaboration with international

colleagues. Several international scholars have already assisted us in preparing this proposal with a view to conceptual as well as empirical issues. These and other scholars that we have contacted informally support our approach and have indicated strong interest in being involved in our work in the future.

There are specific opportunities for gaining input and disseminating our output in an international arena. First, the 21st EGOS Colloquium in Berlin in July 2005 will focus on “Unlocking Organizations” and has a number of subthemes that we could contribute to (e.g. “Path Dependence and Creation Processes in the Emergence of Markets, Technologies and Institutions”). Secondly, we will be able to organize an international workshop in 2006 under the auspices of the European Institute for Advanced Studies in Management (EIASM). Thirdly, we aim to organize a session on innovating NGL at an Annual Meeting of the Academy of Management in the U.S. towards the end of the project. In the second half of the project, we will disseminate and discuss our work in a workshop with managers and policy makers.

The research project is planned for a period of five years with three intensive interview phases. This will enable us to study the process of innovating NGL in real time up until the point when the new system technology is expected to be introduced in volume production in 2009. The exact timing of our intensive interviewing phases will be scheduled and, when necessary, adapted to coincide with key milestones in NGL development as expected by experts.

The proposed project will be embedded into the activities of the Research Group on Inter-firm Networks originally established by Jörg Sydow at the Free University of Berlin in 1996. Arnold Windeler was coordinator of this group from 1996 to 2001. He now holds a chair at the University of Technology Berlin and the Research Group continues as an inter-university group. The Research Group has successfully concluded several projects directly relevant to the proposed study.

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