Optoelectronics in Scotland: Network Reconfiguration in a Sectoral System of Innovation

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Abstract: Optoelectronics (or photonics) has developed as a significant enabling technology central to the operation of a wide range of artefacts evident in telecommunications, consumer electronics, medical devices and defence. Policy makers in several nation states and regions have been keen to develop capability in optoelectronics given that these technologies may be widely leveraged in such high-value sectors. The paper explains reasons for the emergence of optoelectronics activity in Scotland. A sectoral system of innovation approach is used to explain the activities of optoelectronics actors in Scotland. The Scottish optoelectronics sector has survived significant exogenous shocks and there is evidence of enduring local geographic connections within the network coupled with international interactions. Reactive and proactive strategies of firms and other actors within the cluster have enhanced articulation to international value chains of knowledge and technology production.

As in many other locations with significant optoelectronics activity, Scottish firms tend to be geographically clustered. The use of value chain and industry architecture frameworks has been applied to the sectoral systems of innovation construct in order to bring additional explanatory power to the dynamics and power asymmetries in the cluster. Distinct patterns are evident between the set of firms which engage in final products (essentially acting as system integrators) positioned towards the end of the value chain, compared with the set of firms positioned earlier in the value chain (predominantly reflecting producers of materials and components). Firms positioned early in the value chain have experienced significant shake-out and attrition with survivors displaying dynamic capabilities as part of a network reconfiguration which maintains local interactions while permitting new non-local interactions.

Keywords: innovation, clusters, networks, optoelectronics, value chain, policy

1. Introduction

The paper is structured as follows. The nature of optoelectronics and its development as a fusion technology are briefly described. The historical roots of the sector in Scotland are set out, with identification of a geographic clustering of activity. Given that the optoelectronics sector is characterised by technological intensity and specialisation with often fragmented value chains at both local and international levels, the nature of innovation resulting from this multiplicity of user-producer interactions is of interest. In order to examine this, and following a summary of the wider innovations systems construct, a sectoral system of innovation approach is used to identify and explain network configuration within the Scottish optoelectronics sector. In the aftermath of a significant period of disruption in the global optoelectronics sector, the discussion moves to resultant dynamics in the Scottish optoelectronics value chain, and consequent adjustments to relational architectures and user-producer interactions.

2. Optoelectronics technology development

Optoelectronic devices have emerged from the junction of knowledge in three distinct fields: quantum theory; the production of new materials; and the physics of semiconductors (Nosov, 2002). Optoelectronics is a set of technologies and activities which incorporates and combines core optical and electronic functions within artefacts ranging from components to complex product systems. The fundamental scientific principles of the technology are emphasised by Hendry and Brown (2006, p. 710) when they state that optoelectronics involves "…the manipulation of photons (light) and their interaction effects with electrons". The terms 'optoelectronics' and 'photonics' are both evident and are often used inter-changeably. For example, De Martino et al (2006, p.11) state that… "photonics, also referred to as optoelectronics, may be defined as the 'technology of generating and harnessing light and other form of radiant energy whose quantum unit is the photon'".

The wide range of sciences which feed-in to optoelectronics and the need for the development of skills which embrace and cross these disciplines (physics, chemistry, materials science and engineering) suggests the increasingly systemic nature of activities within the field of photonics. Among the first to recognise the 'integral' (indivisible and independent) nature of the technology and its wide application was Sternberg (1992) and this has resonance with the concept of 'technology fusion', which according to Kodama (1992, p.70) "…blends incremental technical improvements from several previously separate fields of technology to create products that revolutionise markets". Establishing a shared view on the boundaries to the optoelectronic sector is something of a challenge. Miyazaki (1994) has proposed a three level categorisation comprising: generic technologies and materials; key components; and end-user products and systems.

Hendry, Brown and Defillippi (2000, p.136) describe the nature of the sector as complex with diversified end-markets and this may account for the observed fragmentation within the industry. Consequently these authors argue this has encouraged collaboration between small and large firms with the latter acting as 'systems integrators' (see Prencipe, Davies and Hobday, 2005) providing a degree of focus and co-ordination for the network. A further difficulty in researching the available data on optoelectronics lies in the range of classifications, technologies, applications and end-user products. A systematic approach is needed in an attempt to confine or capture these. Several sources (Miyazaki, 1994; Hendry, 1999; Hendry, Brown and Defillippi, 2000; DTI, 2006; and Sydow et al, 2007) have attempted to delimit these activities.

3. Optoelectronics – historical roots and economic policy in Scotland

Scotland has contributed to fundamental historical developments in optical sciences and theories of electricity and magnetism (Marsh, 2002). This includes: scientific knowledge from the experimental work of Sir David Brewster (1781-1868); William Thomson (Lord Kelvin) at Glasgow University and the development of a dynamic theory for electricity and magnetism by James Clerk Maxwell (1831-1879); and the discovery by John Kerr (1824-1907) of electrically induced optical phenomenon, whereby strong electrical fields alter the molecular structure of glass. Scottish engineered optical heritage can be traced back to the 1890s with the production of optical range finders in Glasgow (Mathas, 2002) and links with the defence industries via the creation of the firm 'Barr and Stroud' of Glasgow. This selection of examples provides evidence of strong links between Scottish science, engineering and innovation which hints at a local and enduring systemic capacity for the creation and nurturing of technology fusions incorporating key building blocks of these technologies.

The loss of traditional industries from Scotland during the 20th century prompted an active search for new industrial settings to replace and upgrade value generation within the economy. Policies designed to embed new industries have been subject to widespread, but not universal, criticism as Scotland has tried to create indigenous value chains by attracting multi national enterprise (MNE) consumer electronics system integrator firms. Significant market turmoil in the key information and communications technologies (ICT) markets has caused readjustment of optoelectronics activity: not just in Scotland, but throughout global supply chains. Much of the present concentration in such high technology industries is associated with the 'Central Belt' area of Scotland. This comprises locations ranging from Dundee south and westwards to Inverclyde, the urban areas of Edinburgh, the new towns of Livingston, East Kilbride and Glenrothes plus Greenock and Glasgow. These historical and spatial settings have largely been maintained and reinforced over time as a consequence of policy instruments which have pursued network, cluster and system-like dimensions to the Scottish optoelectronics sector, initially with aim of producing vertically integrated supply chains (Sutherland, 2009).

4. Innovation Systems

The 'innovation system' approach is a fundamental construct for describing, understanding and explaining the nature of innovation (Edquist, 1997). The primary intention of the approach is to identify actors, networks, institutions, dynamics and the overall performance of the system with regard to innovation. Interactions between actors and elements in the system (and the extent to which these interactions may promote innovation) are central, as is the evolutionary processes which may promote and sustain the system. The importance of social interaction for influencing economic activity (Granovetter, 1985) and the notion of user-producer interactions (Lundvall, 1988) provide a primary mechanism for innovation within innovation systems.

4.1 Methodological and analytical constructs

Carlsson et al (2002) explored methodological and analytical issues surrounding the innovation system approach. Technological aspects of these have been investigated by Bergek et al (2008) with respect to functional dynamics. Policy makers have engaged with the innovation system concept at a variety of spatial levels ranging from the supra-national (such as the European Commission and the OECD) to national, sub-national (regional) and local levels (where local economic development agencies have employed the innovation systems approach for various purposes). This level of approval has in turn resulted in a wide range of policy interventions designed to promote innovation. Such interventions are often directed towards network or system-like considerations. This diffusion of system-based policies and the consequent requirement for appropriate evaluation (Bellandi and Caloffi, 2010) presents particular challenges to policy makers given the evolutionary and often complex nature of the system under consideration.

The innovation systems approach has fragmented into a number of concepts, comprising: *national* innovation systems (Freeman, 1987; Lundvall, 1988; Nelson, 1992); *regional* innovation systems (Cooke et al, 1997; Autio, 1998; Asheim et al, 2011); *technological* systems (Carlsson and Stankiewicz, 1991) and *sectoral* systems of innovation and production (Breschi and Malerba, 1997; Malerba, 2002). Given this family of concepts, scholars must identify the appropriate unit of analysis for investigation, and these selections remain contested within the literature. The wider systems of innovation approach has been criticised for conceptual diffuseness with a need for it to become more theory-like. This paper has adopted the sectoral system of innovation approach as the de facto entry point for the study.

4.2 Sectoral systems of innovation

Sectoral innovation systems are seen by Breschi and Malerba (1997) as an alternative way of thinking of industry-level innovation processes. A sectoral system of innovation is defined by Breschi and Malerba (ibid., p.131) as "…that system (group) of firms active in developing and making a sector's products and in generating and utilizing a sector's technologies; such a system of firms is related in two different ways: through processes of interaction and co-operation in artefact-technology development and through processes of competition and selection in innovative and market activities". Malerba (2002, p.248) then provides a somewhat broader definition of sectoral systems of innovation (and production) as "a set of new and established products for specific uses and the set of agents carrying out market and non-market interactions for the creation, production and sale of those products". Carlsson et al (2002, p.236) state that it is possible in principle "to view a national system of innovation as the aggregate of a set of technological, sectoral, or regional systems". Given these definitions (and the afore-mentioned multiple product lines and applications which feature optoelectronic technologies as being central to their operation) a case is made for using the sectoral innovation systems analytical construct in the examination of innovation in optoelectronics activities. In essence, a 'knowledge field' has been adopted as the focusing device (after Bergek et al, 2008) within the spatial domain of Scotland.

4.3 Data gathering for the study

Interviews were conducted with actors selected from across the optoelectronics sector, comprising: policy makers; trade associations; academics; entrepreneurs; research directors; and strategic managers of firms of different scales of operation within Scotland ranging from slam spin-put firms to large MNEs. The purpose of the interviews was to establish the sectoral innovation characteristics of optoelectronics within the region. The themes of the survey drew on the extent to which interactions occurred and were distributed between actors within the system and to identify how these had changed due to the turbulence within the sector.

5. Network relations and dynamics in the Scottish optoelectronics sector

In an investigation into the scale and heterogeneity of Scottish optoelectronics firms, Sutherland (2009) has pointed to a diversity of activities with resources being deployed variably within firms in the sector. That study demonstrated a trend in the first decade of the 21st century of an increased contribution from small and medium-sized enterprises (SMEs) coupled with a decline in large MNE firm presence but a reducing economic contribution from the sector within Scotland overall.

The recent context of optoelectronics activities and events associated with exogenous change and structural adjustments to practices in production have had significant impact. The structure of the following discussion draws on framework components proposed by Malerba (2002) which set out the basic elements of a sectoral system of innovation coupled with the Bergek et al (2008) approach in examining key processes, or 'functions', for analysing innovation systems.

5.1 Products

Products which feature strongly within the Scottish sector include lasers, displays and sensors. These artefacts can be leveraged in a wide number of intermediate and finished products ranging from commercially-available devices such as mobile phones through to complex products for industrial markets. Final system integrator firms within Scotland operate in defence, telecommunications, computer and medical sectors as well as astronomical instruments and measurement devices.

5.2 Knowledge and learning process

Universities continue to play a key role in knowledge production close to the core science of optoelectronics technologies. The sector has mobilised human capital by the development of research and educational opportunities closely aligned to the knowledge base of the sector and also in the development of club goods and complementary assets. Large firms are considered to have greater capacity to initiate and support external optoelectronics research activity. These large firms are considered to be less reliant on the success of individual R&D projects compared with small firms. The reason provided for this assertion comes from the belief that SMEs often have a single focus based on their own individual and limited resources and capabilities. The imperative for successful research is heightened for these firms as a positive outcome offers the prospect of early development and translation into innovative products. By contrast, large firms can often be content with negative outcomes as part of a refining and proving process over an extend timescale of several years. Given that many of the available policy initiatives are targeted at SMEs, research establishments are often led to working with SMEs under more pressurised conditions and claims are made that such projects often do not cover costs. Firms report the loss of a tier of knowledge at the component level because of the collapse of this part of the value chain, resulting in radical change to the remaining actors within the system. This has prompted a requirement for business knowledge and scanning of sources of technical knowledge. With manufacturing increasingly being outsourced and offshored via a geographically distributed value chain, there is a growing realisation that knowledge is the most important value-adding element within the system.

For MNEs, a concentration of knowledge assets in fewer locations is evident and some concern is expressed that Scotland may not be able to retain these system integrator facilities. Such decisions are taken centrally by headquarters offices regardless of what is happening in local clusters. Knowledge heterogeneity is evident and actors see the need to link these sources of knowledge for innovation. The presence of heterogeneity is seen as an opportunity to make novel connections that have potential to deliver significant value in the future. The knowledge requirements are considered to increase with time as a consequence of complexity. Firms report some fuzziness in boundaries with respect to being able to delineate distinct phases of R&D, and, in such cases, firms report making regular and incremental interventions which may inform future research. Actors that provide bridging between with others in the system see the creation of new knowledge as an imperative for their own organisations and for the wider optoelectronics community in general. These bridging institutions are considered to be conduits for subsequent knowledge transfer.

5.3 Actors

Organisations which bridge between research and industry by providing activities in the 2 to 5 year space between research and the market include: The Strathclyde Institute of Photonics; the Photonics Innovation Centre at St Andrews; the Scottish Microelectronics Centre at Edinburgh University; and the Thin Film Centre at UWS are identified. These organisations have remained as important providers of research and technical advice within the sector. Consequently it can be stated that universities are an enduring feature of the Scottish system.

Entrepreneurial activity and experimentation have been evident, particularly with the development of scientific entrepreneurs enabled by the prevailing supportive appropriability regimes in universities in the Scottish Central Belt. There are a variety of these entrepreneurial developments within the sector, however, several are observed to be closely linked to display technologies. Optoelectronics activity has been legitimised with the development of an active trade association (the Scottish Optoelectronics Association) and ongoing proclamations from economic actors such as Scottish Enterprise as to the importance and viability of the sector.

Large firms are identified as having significant influence over the optoelectronics value chain in Scotland and their involvement in the complete product development cycle is seen as pivotal. The pool of large firms in Scotland has diminished since the year 2000. Those remaining are predominantly in defence markets. These defence markets can be considered to have some degree of protection from market forces, however, they are subject to political decision-making and have also undergone changes with the restructuring of defence research and supplier networks. There is evidence of local search for expertise from these large defence system integrator firms with respect to research, development, instrumentation and maintenance as well as support for development of training and academic qualifications in the workforce via universities. In the past there has been a significant mobility of the workforce circulating within defence firms in the local community. This pool of knowledge and expertise is observed to spillover into SMEs in both defence and non-defence activities.

5.4 Mechanisms of interaction

Fragility has been exposed in the Scottish region that may be linked to initial policy ambitions to deliver complete local value chains. These policy imperatives, focused on creating the development of vertically integrated optoelectronics activities within Scotland, have had to face the realities of more global interactions characterised by intermediate goods and modularity coupled with the challenge of connection to geographically distributed international value chains. This dynamic has changed user-producer engagement within the system which optimises regional network interactions in the cluster while also linking to international networks. Such international connections reflect the evolution of firms and their innovation strategies in response to external challenges.

Policy discussion cuts across a range of issues which impinge upon firm creation, location decisions, growth, innovation and value chain configuration. Policy influences clustering. Indeed policy initiatives have been specifically designed to have consequences for the clustering of firms and the completeness of the optoelectronics value chain within Scotland. Policy initiatives are viewed variably by firms within the system. For SMEs there is a higher dependence on these programmes and founders of some of the smaller firms confirmed that their organisations would not have been formed without the funding that ensued. The Scottish Co-Investment Fund was identified as being of particular relevance in this respect. Involvement and regular engagement with Scottish Enterprise is seen as important by SME firms. From the SME perspective, European funding was viewed as being bureaucratic and time consuming to initiate. There was acknowledgement that these programmes could act as gateways to collaboration but the extent to which funding filtered through to SMEs was considered to be low.

Firms report more formality appearing in relationships between actors in the system. The negative consequences of this lie in additional spent time, with resources increasingly directed towards intellectual property discussion and negotiation. There is recognition that relationship building is desirable and important in order to sustain connections over time, particularly as a means of negotiating and overcoming technical problems. Informal links are also in operation in parallel with the more formal activities. Informal links bring ideas for potential projects which may be instigated through more formal arrangements in the future. By contrast, some firms report that new ventures may require more open-book collaborations with SMEs and, rather than paying market value for services, these relationships are built on the prospect of mutual gain and thus require shared expectations combined with significant levels of trust.

Given the recent turmoil in the sector, small firms are increasingly engaging in an evaluation of prospective customers, in effect doing due-diligence to assess their likely longevity and chance of survival and to justify allocation of resources in relationship-building.

Small firms report increased levels of collaboration for innovation. Large system integrators are perhaps more conservative with respect to collaborations and may not be attuned to changes in frequency or type of collaborations. The facilitation of collaborations in science-industry bridging organisations is a fundamental aspect of their activities. The selection of partners for research consortia is informed by the track-record and capabilities of partner institutions. These actors report that funding of opportunities are more open to competitive forces. In general, an overall ‘want’ to collaborate is evident and this is reinforced by the availability and tenor of policy instruments which encourage multi-actor programmes. Firms have multiple collaborations in place at any one time. Given the time and resource required to initiate and maintain collaborative projects, firms engage in significant partner selection activities. Collaboration between departments within universities continues to offer challenges. International collaborations are seen to be desirable as they offer the potential to access sources of new knowledge. However, these programmes are frequently seen as problematic because of legal negotiations relating to intellectual property issues and the apportionment of the shared benefits of innovation. Participants in collaborative projects are conscious of the benefits of engagement and this offers the prospect of accelerating involvement in projects over time.

5.5 Processes of competition and selection

Changes to the climate of technological opportunities prompted by the shocks to the ICT market caused a rapid adjustment to supply chains with corresponding impacts to the optoelectronics value chain. In particular, those firms and activities associated with component production and other early stage activities in the value chain saw significant loss of firms within that part of the system. However, post-disruption, SME firms overcame difficulties of scale to engage with large international firms as it takes time to persuade large firms to initiate a relationship and resources are required to build rapport. Such relationships are highly valued by Scottish firms as they permit access to key resources outwith Scotland which are not present in the cluster. The sector is shifting from a vertically integrated pattern to an outsourced chain. Management of, and articulation in to, this chain is becoming an important consideration for incumbent firms.

The dynamics in the sector are evident in a number of trends. There is decamping of major players, predominantly system integrators, from Scotland and the UK. This is particularly pertinent to ICT markets and confirms the dynamic and global nature of the sector and the lack of embeddedness of MNE firms with the Scottish cluster. Allied to the relocation dynamic of MNE firms there is also evidence of firms closing - either in a controlled manner or going into receivership. Merger, acquisition and disposals have been apparent as firms respond to the recent selection environment. The study also points to a brain-drain away from Scotland to more attractive academic and engineering opportunities in other UK and international locations. This was perceived to be problematic as regards the available knowledge base and prospects for innovation.

International relationships are of increasing importance as a means of accessing specialised knowledge and capabilities which are absent at the local level and also as a source of manufacture at lower cost than can be achieved locally. In addition to directly initiating R&D projects, actors are also seen to sponsor R&D ‘club’ projects and some use un-solicited speculative research proposals as indicators of the sources and development of knowledge within the sector. Cost-reduction is a current primary driver for innovation in optoelectronics, particularly if linked to telecoms and consumer electronics markets. For example, the use of integration of devices onto single chips (System on Chip (SoC) technology) is emerging as one area demonstrating immediate cost advantages.

5.6 Institutions

Increasing complexity embodied in devices and processes such as SoC is being paralleled by increasing complexity in relationships between actors. The impact of this development on firms is that design, manufacturing processes and device issues cannot easily be separated-out as has been the case in the past. The consequence for firms is that they have to engage with other actors in the system to plug resultant knowledge gaps.

Complexity of retaining intellectual property rights in outsourced models is evident as a consequence of extended value chains. Thee desire to protect the chain actor’s intellectual property has ramifications for feedback completeness, with some firms reluctant to provide suppliers with knowledge that could enhance the supplier firm’s products. This may limit directed innovation flowing from relevant improvement analysis. This suggests that user-producer interactions may not always provide a stimulus for innovation.

6. In conclusion

Innovation in the Scottish optoelectronics sector can be described using a sectoral innovation system construct. The sector has developed in Scotland by building on historical capabilities in optics, physics and engineering in order to successfully underpin a diverse set of practical applications. The sector has been subject to exogenous shocks and this has resulted in a shake-out of actors within the system, particularly in the part of the sector which is strongly linked to local production of components. This has had consequences for network relations within the Scottish cluster and these are increasingly internationalised and more transactional in nature. Asymmetries in network relationships are evident, and policy arrangements have had to adjust to reflect the reality of supra-national value chains of production. The focus of Scottish optoelectronics firms lies with global markets. The nature of the technology, associated artefacts, devices and end markets require an international focus. This driver, coupled with the widespread desire of firms to grow companies of high value, is widely perceived to create an imperative to identify, sustain and further develop international connections. Interactions for innovation also feature an international dimension, while retaining opportunities for local interaction.

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