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ENGTEC 1482 No. of Pages 12
ARTICLE IN PRESS

J. Eng. Technol. Manage. xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Journal of Engineering and Technology Management

Miniaturization of image sensors: The role of innovations in complementary technologies in overcoming technological trade-offs associated with product innovation

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ARTICLE INFO

Article history:
Received 23 January 2016
Received in revised form 2 September 2016
Accepted 19 January 2017

Keywords:
Complementary technologies
Product innovation
Technological change
Miniaturization
Image sensors

ABSTRACT

Miniaturization has been the main driver of product innovation in image sensors and other semiconductor devices for several decades. Strategy and technology researchers, however, have somewhat overlooked the enablers of miniaturization. Using charge-coupled device image sensors as the context, we find that innovations in complementary technologies played a vital role in mitigating the technological trade-offs associated with such product innovations. In the process, we contribute to our understanding of technological evolution by relating the enabling role of complementary technologies to product innovation.

1. Introduction

The importance of complementary assets in technological evolution and change can be traced back to Teece (1986, pp. 285), who noted that such assets helped firms appropriate the value created through product innovation. Subsequently, researchers have noted that complementary assets, such as access to distribution channels and complementary goods, act as buffers during technological transitions (Mitchell, 1989; Tripsas, 1997) and play a vital role in creating value for firms during such changes (Schilling, 2008). More recently, researchers have highlighted the importance of complementary *technologies* (CTs) by exploring the role of such technologies in post-merger performance of firms (Makri et al., 2010), integration of such technologies by startup firms (Anderson and Parker, 2013), and technological progress (Funk, 2013).

These recent investigations of the role of CTs support the rich evidence in the literature that highlight the virtues of *innovations in CTs*. For example, following the oil shocks in the 1970s, machine tools manufacturers with the help of innovations in CTs– the Computer Numerical Control systems– heralded the Toyota (or Just-in-Time) production systems and helped automobile manufacturers create value for customers who demanded fuel-efficient cars (Ayres and Miller, 1981). Consistently, Henderson (1995 noted that innovations in CTs such as "production control techniques, better resist systems and finer control of alignment technology" helped shift the "natural" limits (Sahal, 1985) in the evolution of optical lithography aligners. Similarly, Funk (2013 observed that innovations in CTs helped VHS and Betamax video recorder manufacturers improve the critical performance feature, the "magnetic recording density."

Anecdotal evidences also suggest that the lack of innovations in CTs can create insurmountable roadblocks for manufacturers in their efforts to improve the technological utility of products. For example, although Leonardo da Vinci had

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http://dx.doi.org/10.1016/j.jengtecman.2017.01.002
0923-4748/© 2017 Published by Elsevier B.V.

designed advanced flying machines, these were impossible to manufacture during his time because manufacturing such products required associated innovations in CTs, such as machine tools that were needed to manufacture the components and design the product architectures of such flying machines (Fagerberg, 2005).

Despite the rich evidences highlighting the importance of innovations in CTs, relatively underexplored in the literature is the role of such innovations in mitigating the *technological trade-offs* associated with product innovations, which may be critical for creating customers' value (Puranam et al., 2003). The genesis of research highlighting the importance of trade-offs can be traced back to Skinner's (1969, 1974) pioneering work on manufacturing strategy. Subsequently, Dosi (1988 underscored the importance of technological trade-offs when he noted that the search for solutions in technological innovations is "generally 'focused' by trade-offs involved in the use of machines (e.g., between speed, flexibility to different uses, and cutting precision)." Similarly, Christensen (1997) postulated that addressing the technological trade-offs among the established and emerging product performance features—such as capacity and portability of hard-disk drives—is a critical part of firm's response to a disruptive change.

By combining the importance of mitigating technological trade-offs during technological innovation *and* our motivation to understand the role of innovations in CTs in mitigating those trade-offs, we seek an answer to our research question—"*how do innovations in complementary technologies help firms create value by mitigating the technological trade-offs?*" If successful, our endeavor will extend Dosi's (1988; p. 1129) observation– that "engineers typically try to improve the desirable characteristics that are specific to a certain product, tool, or device, keeping in mind the *trade-offs* among them"– by highlighting that innovations in CTs are critical to mitigating such trade-offs while improving the desirable characteristics of new innovative products and helping new technologies "progress" along their technology trajectory (Dosi, 1982).

The context of our study is technological innovation in semiconductor-based image sensors, which are extensively used in digital cameras and have been the hotbed of technological change (Fossum, 1993). Prior research on semiconductor devices (see e.g., Mollick, 2006) suggests that miniaturization has been the "main direction" of technological innovation in the semiconductor industry for over six decades (Epicoco, 2013) and has affected "all kinds of technology, from home entertainment to space exploration" (Wong and Iwai, 2005).[1] Semiconductor-based image sensor is one such device that has been affected by miniaturization. The improvements in resolution of digital camera sensors (e.g., Nikon's sensors' resolution were 1MP in 1990; 6MP in 2002; 10MP in 2005) are the result of miniaturization. Thus, to seek an answer to our research question, we concentrate on miniaturization of Charge-Coupled Device (CCD) image sensor. The importance of innovations in CTs, such as electron beam lithography and microlens, which helped manufacturers overcome the technological trade-offs associated with miniaturization of CCD image sensors, makes this an ideal context to understand the role of innovations in CTs as the driver of product innovation.[2] We follow Suzuki (2010) and define CTs as product or process technologies that help firms mitigate technological trade-offs, which firms confront while improving the critical performance feature (Christensen, 1997) of a product. As Suzuki (2010 noted, the critical performance feature of image sensors—photosensitivity or image quality– increased "ten-fold per decade" since the 1970s through innovations in the "devices and process technologies for improving image quality."

To seek an answer to our research question, we follow Holbrook et al. (2000) and Eggers (2014) and rely upon archival data, interviews, published and unpublished accounts of industry experts, and information from secondary sources. Additionally, we adhere to the basic tenets of grounded theory building as suggested by Glaser and Strauss (1967) Glaser (1999) and Eggers (2014). Accordingly, first, we reviewed all documents available from secondary sources and analyzed the events to identify core idea of our story. Thereafter, we counterchecked our interpretation with several industry experts. We are indebted to Dr. Eric Fossum, Dr. Albert Theuwissen, and others for helping us understand the technological changes in the industry. Such a process helped us to "present facts and ask questions" and counter-questions "about possible explanations of these facts" (Bettis et al., 2014)).

Next, we discuss the literature, followed by a description of the context.

2. Literature review and theory

2.1. Technological innovation and its role in value creation

Innovation researchers have a rich tradition of exploring the sources of innovative ideas and firm-level competencies that act as the genesis for technological innovations. Prior research (e.g. Foster, 1986) notes that technological progress happens along a predictable S-curve trajectory and follows a cyclical pattern, as predicted by Abernathy and Utterback (1978). Dosi et al. (2000 noted that the "mainstays" of the technological evolution and innovation literature are Tushman and Anderson (1986) and Henderson and Clark (1990)—"two papers that describe different conceptual litmus tests for when new

[1] Nobel Laureate in Physics, Richard Feynman, had predicted this trend and coined the term "miniaturization" during his lecture titled "There's plenty of room at the bottom: An invitation to enter new physics," which was delivered at California Institute of Technology in 1959. Subsequently, in 1965, Gordon Moore predicted the rate of improvement of microchip density.

[2] Although we concentrate on CCD sensors in this paper, it is worthwhile to mention that Complementary Metal Oxide Semiconductor (CMOS) sensors have replaced CCD as the consumer digital camera image sensors since the late-2000s (e.g., in 2009 Nikon introduced its last CCD DSLR camera—Nikon D3000). Currently, CCDs are used in space applications such as the James Webb Telescope, which will be launched by NASA in 2018. Nonetheless, a close examination of the evolution of CCD sensors can shed much needed attention to the role of innovations in CTs for product innovation.

Please cite this article in press as: R. Roy, J. Miller, Miniaturization of image sensors: The role of innovations in complementary technologies in overcoming technological trade-offs associated with product innovation, J. Eng. Technol. Manage. (2017), http://dx.doi.org/10.1016/j.jengtecman.2017.01.002